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Removing fouling residue from molds in-the-press with CO_2 pellet blasting.

The use of CO_2 solid particle blasting for non-abrasive cleaning of rubber molds without removing molds from the press or creating a secondary waste stream has intrigued molded rubber products manufacturers since the mid-1980s. Today, many molded rubber product manufacturers are aware of CO_2 particle blasting technology and its potential to reduced production downtime, maintenance labor costs, and enhance product quality and appearance. In fact, molded rubber products manufacturers make up a major segment of the CO_2 particle blast cleaning equipment market worldwide.

While working to develop applications solutions for molded rubber products industry, CO_2 blast cleaning technology suppliers began to find solutions for the general problems of noise, ergonomics, operator safety, work area accessibility, system reliability and operating costs. Within the molded rubber products industry, the economic impact of implementing CO_2 particle blast mold cleaning is overwhelmingly significant and the cost to benefit analysis usually indicates a payback in terms of months, not years.

The following discussion will provide an understanding of the state-of-the-art solid CO_2 particle blast rubber mold cleaning technology. From a cost-to-benefit standpoint, solid CO_2 particle blast mold cleaning is, more often than not, shown to be the best choice among the many methods and technologies currently available for rubber mold cleaning. Within the CO_2 particle blasting industry, however, there are a variety of technologies that offer different levels of mold cleaning cost and performance. Similar to abrasive blasting equipment, there are two types of CO_2 particle blast systems. One type is the direct feed or "single-hose" system. The other is the inductive feed, or "two-hose" system. In abrasive blast systems there may *not* be significant cleaning performance differences between the two types of systems. However, for CO_2 particle blast systems there is a dramatic performance differential between the types; and the differences must be fully understood and considered before selecting a mold cleaning system. There are also two basic forms of the solid CO_2 blasting media that must be understood. There are discrete "pelletized" dry ice particles, and shaved dry ice "flakes" produced from a block of dry ice.

The mold cleaning performance levels of the different types of CO_2 particle blast systems and CO_2 media are very significant. Failing to understand these fundamental differences may lead to the selection of an inappropriate system and a significant reduction in potential productivity increases and cost savings.

Why Rubber Curing Molds need to be cleaned

A major problem faced by all molded rubber products manufacturers is that of mold fouling, a residue build-up on the curing surfaces of rubber molds caused primarily by chemical reactions of the release agent, or the adhesive used for rubber-to-metal bonded parts, with the base polymer under heat and pressure. For injection molding systems, a major area of concern is keeping mold surfaces that mate or come into intimate contact during cure, free of residue build-up to minimize flash. For multi-section rubber molds, these are the surfaces between the mold sections that come in contact when the mold is closed and produce parting lines in the part. If too much residue is allowed to build up in this area of the mold, the mold sections will not mate together completely, even under the extreme press squeeze pressure. The result is a noticeable "flash" at the parting line on the surface of the product. An excessive amount results in additional labor costs to remove the flash. For molds that are designed to be flashless / trimless, keeping the precision mating surfaces free of fouling is even more critically important. Excessive fouling residue build-up in intricate details and in sharp edges or corners of molds can cause the parts to loose details (lettering, logos, etc.) and critical cross sectional shapes (seal lips, o-ring cross section, etc.), all resulting in scrapped parts.

Excessive build up of release agent in the cavities can cause high releasant transfer to the parts, resulting is surface gloss level deficiencies like glazing, etc. As much as the release agent can benefit the rubber molding process, an excess of it in the cavities can be detrimental to the process.

Another problem area, especially in injection and injection transfer molds, is the clogging of sprues, runners, gates, and vents with fouling residue, overbuilt-up mold release residue, and semi-cured rubber. Clogged vents can cause non-fills and other serious part defects. Finally, the overbuild-up of mold release agent residue or adhesive residue used in rubber-to-metal bonded parts can cause defects like knit lines and surface gloss loss, or even cause the parts to stick in the mold and tear upon removal.

Comparing Costs to Benefits

As an example, a current user of CO_2 pellet blast mold cleaning technology in the rubber industry conducted and in depth cost-to-benefit analysis to compare the value of CO_2 blasting with the abrasive blast method already in use at his facility. This study was conducted after completion of a trial usage period with a CO_2 pellet blasting system, and before the final purchase of the CO_2 system. This user took into consideration all aspects of capital and operating costs, including purchase price of the CO_2 blasting equipment, CO_2 pellet usage and cost vs. abrasive media, compressed air and electricity costs for both types of systems over time, mold and press downtime for cleaning with both types of systems, and other aspects of mold maintenance costs relative to his operation. CO_2 pellet blasting can be accomplished in-the-press in one-tenth to one forth the time required for traditional off-line methods. Interestingly, the cost-to-benefit analysis was presented to the company management in terms of "increased product sales dollars per day" by using CO_2 pellet blasting instead of their existing off-line abrasive mold cleaning method. The study indicated that the "lost sales dollars due to mold cleaning" would be decreased by 75% every day. In other words, whatever total parts sales dollars were being "lost" each day due to press downtime were cut to only $_2$5% of that amount by adopting CO_2 pellet blast cleaning technology for all of their molds. Based on this increased productivity ratio, the user determined complete pay-back on a portable CO_2 pellet blast mold cleaning system would be realized in under 60 days. Other cost to benefit studies have been conducted by rubber product manufacturers with comparable results, and given the similarities in the manufacturing processes of most rubber molders, this level of increased productivity and payback is typically experienced when abrasive mold cleaning is replaced with CO_2 particle blasting technology.

Mold Condition Factors That Effect Cleaning Performance

Temperature

Data gathered over the past decade, since the emergence of CO_2 particle blast cleaning in the molded rubber products industry, supports the fact that rubber molds between 300^o F and 350^o F, can be cleaned 3 to 4 times faster than the same molds at ambient temperature (cold molds). Although the reasons and mechanisms which give rise to this phenomenon are not completely understood, mold cleaning experience in curing departments at many different rubber products manufacturers have proven this to be the case. In case studies involving Rubber Mold Fouling, particularly with EPDM, FKM, NR, NBR, HNBR, Butyl compounds, and flouro-elastomers, it has been determined that the reactive chemicals present in the base polymer, the chemicals in cure accelerators and inhibitors, and the chemicals in many mold release agents combine at the curing temperatures to form an almost glass-like material at the product-mold interface. This glass-like material is different from the polymer material of the cured product. The glass-like property of this fouling residue at elevated temperatures allows it to be easily removed from the mold surface and fractured into small particles by inducing high levels of thermal stress, or "thermal shock " with CO_2 pellets. Since the temperature of solid CO_2 is -109 ^{o} F, the CO_2 pellet blast stream is an ideal source for inducing thermal shock in the residue layer. At lower temperatures (below 150 ^{o} F), the fouling residue can become much more difficult to remove from the mold surface because it resembles a very dense visco-elastic material which absorbs the impact energy of the CO_2 pellets. The thermal shock mechanism becomes less effective because there is very little temperature differential between the material and the mold surface. The overall result is that it may become very difficult to remove the fouling residue from room temperature, or "cold", rubber molds, and sometimes the residue will not respond to the CO_2 particle blasting at all.

Figure 1 - Typical Mold Fouling Caused By Rubber-to-Metal Bonding Adhesive

Adhesive Fouling of Molds Producing Rubber-to-Metal Bonded Parts

Many rubber products, especially in the automotive and vibration mount markets, consist of a rubber isolation shape molded around and bonded to a steel mounting plate or a cylindrical center steel tube. These rubber-to-metal bonded parts require a heat activated adhesive applied to the metal portion which creates an incredibly strong bond between the metal and rubber during the curing cycle. The concern with this process is that the heated adhesives become almost liquified at curing temperatures and the excess flows out of the part during the high temperature curing cycle, creating a large amount of rapidly built-up fouling on the mold surfaces. See Figure 1, below, which shows typical rubber-to-metal bonding adhesive fouling on a mold surface.

Fortunately, this type of "baked-on" adhesive fouling also resembles a glass-like residue that responds exceptionally well to the temperature gradient induced "thermal shock" removal mechanism of CO_2 pellet blasting. Rubber-to-metal bonded part molds can be cleaned in the press as often as once a shift if necessary, so CO_2 pellet blasting offers the rubber-to-metal bonded part manufacturer a safe, easy to use, and extremely cost effective way to keep these molds in continuous production.

Mold Metallurgy and Temperature Effects

Early on, valid concerns were expressed by rubber product molders about the possibility of mold sub-surface damage resulting from thermally induced changes in the metallurgy of the mold material. This concern was strong where martensitic and other heat-treated and hardened alloy tool steels are used, as well for certain precipitation hardened aluminum alloys. University and independent laboratory metallurgical studies were funded and performed by several "CO_2 blast cleaning early adopter" rubber molding companies in the mid-1990s. The specific findings in these reports are proprietary to the companies that paid for the studies. In general, the conclusions drawn were (1) no metallurgical changes to the martensitic or alloy hardened structure of the tool steel molds were found after many cycles of CO_2 pellet blasting, (2) the sub-surface thermal gradient in tool steel was negligible (low thermal conductivity), so the mechanism to promote micro-cracks was considered non-existent. In aluminum molds, which have higher thermal conductivity and generally smaller thermal mass, the cool-down (thermal gradient) was greater and more pronounced, but no changes in the precipitation hardened structure were discovered after many blasting cycles. Aluminum mold surface erosion was also considered.

Mold Surface Condition

Abrasive blast media, like plastic or glass beads, typically leaves a "bare metal" appearance after residue removal, even on steel molded rubber products molds. This "like new" appearance is deceiving because it is achieved at the expense of removing a small amount of metal from the mold surface, and by imparting a much "rougher" (more micro "peaks and valleys") surface finish into the mold from the chiseling effect of thousands of abrasive impacts. The rough surface creates an "anchor pattern" that was not present in the original mold surface. This causes fouling residue to adhere and accumulate at an even faster rate than it did on the original mold surface. This mold surface "erosion" will be in discussed later in more detail, but it is evident that what appears to be a "clean mold" surface is a step toward decreasing the useful life of a very expensive production tool.

Flashless / Trimless Tooling

Many rubber product molding companies are currently using, or are considering using, precision designed tool steel flashless / trimless molds. Rubber flash at the tool parting lines, of course, requires additional manufacturing processes to remove it, requires additional quality assurance (inspection) steps to monitor the level and effectiveness of flash removal, creates scrap rubber which must be handled and accounted for, which all adds to the overall production cost. Also, some types of rubber parts have such critical surface finish and dimensional tolerances that only flashless / trimless mold technology can be used to produce them. Flashless / trimless tooling virtually eliminates part flash and it's associated margin-reducing production costs, but the capital cost of the tooling is much higher, and the precision mating surfaces of the molds must be maintained without misalignment, knick damage, or erosion for the life of the tooling. Abrasive particle blast cleaning of flashless / trimless tooling typically cannot be tolerated because of the risk of tooling erosion and damage. Non-abrasive CO_2 particle blasting can be used for hundreds and even thousands of cleaning cycles with NO tool wear experienced.

Non-Abrasive Aspects of CO_2 Particle Blasting

CO_2 particle blasting does not abrade or erode the surface of common mold materials like tool steel and hardened aluminum. Since CO_2 particle blasting only removes the residue on the mold's surface and not any surface metal, any dark stains from cured molded rubber products compounds will remain on the mold's surface, especially on steel tooling. Following CO_2 particle blasting, a functionally clean, residue free molded rubber products mold may not at first appear clean by the old standard of a bright, bare metal surface. The proof of the mold's cleanliness will be seen when the first molded rubber products are cured and inspected for the sharpness of the molded-in details (especially under-cuts and acute angle seal surfaces), and rubber surface gloss level.

Many rubber molds must be "seasoned" with release agent immediately after abrasive cleaning. This usually involves running three to five cycles of parts with sprays of release agent in the cavities after each cycle until enough of a very thin layer of release coat fills in the "valleys" of the roughened surface. All of the parts run during the seasoning process are scrapped because of surface gloss defects, etc. Using CO_2 pellet blasting to clean molds will, over time, shorten or even, as reported in some instances eliminate, the mold seasoning time and resulting scrap. This is because the mold surface will not be severely roughened during each cleaning cycle, and because the energy level of CO_2 pellet blasting can be adjusted to allow for the retention of the seasoning coating.

As stated earlier, chemical stains in the mold metal typically cannot be removed by non-abrasive CO_2 pellet blasting. Severe chemical stains which can leach out of the more porous mold metals to cause "blooming" on the parts may be beyond the ability of CO_2 pellet blasting to counteract. Severe chemical staining of the molds may, in some cases, be significantly reduced overtime by using CO_2 pellet blast cleaning which does not continually open up the surface pores like abrasive blasting does. As the surface roughness goes down and the pores close up over time, stain leaching and stain related defects should diminish as well.

Mold Erosion and Damage Studies

The most well known and widely used method of rubber and tire mold cleaning is abrasive particle blasting. This method is very cost effective, easy to install and maintain, and relatively easy to use. All forms of abrasive blasting MUST be done in an enclosed structure to prevent the distribution of fine airborne abrasive dust particles within the factory environment, and to capture and recycle the spent media. The most popular abrasives used to clean rubber molds are glass, plastic, metallic and ceramic beads. These media have gained acceptance in the rubber industry because they are regarded as only 'mildly abrasive". Other particle blast media used in the rubber industry vary in degree of abrasiveness and subsequent mold erosion, and include silica sand, steel shot, walnut shells, bicarbonate of soda, and abrasive impregnated sponge. All of these abrasive blast media can typically be captured and recycled for use in more than one cleaning session. However, all of these abrasive blast media eventually breakdown (pulverize) into a fine dust which must be disposed of properly to comply with federal regulations. The fact that all of these media types are considered "abrasive" means that ultimately the molds will be eroded to a point where they must undergo extensive rework or be scrapped. Abrasive particle blast mold cleaning is at best, a compromise between a cost effective cleaning method and reduced mold life / continuously declining rubber product quality.

Abrasive, or "mildly abrasive", blasting causes other problems as well. The fine silica imbedded "dust" residue from sand or glass bead blasting, or the imbedded plastic "dust" from plastic media blasting (PMB), can alter the surface of the rubber mold enough to prevent the proper chemical bonding of certain release agents. These mold release agents, which depend on a completely metallic surface to bond to for providing many cure cycles worth of release, are actually pulled off of the mold surface and rendered ineffective in fewer cure cycles because of the "bond blocking" caused by grit residue imbedded in the mold surface. The same type of chemical "bond blocking" can occur when attempting to apply various mold coatings for long term product release capability. In general, all chemicals applied to a metal mold surface react much faster and more efficiently when all of the metal surface is available and not masked by grit residue.

Other non-abrasive mold cleaning technologies that exist, or are emerging, including laser ablation, chemical flushing, and mechanical adhesive bonding of residual rubber. These methods are very much in the developmental stages and do not offer a viable solution to the immediate and near term needs of the molded rubber products industry. Of all the generally accepted "off the shelf " rubber mold cleaning technologies currently available, only solid CO_2 particle blasting has been acknowledged to be non-abrasive, cost-effective, and not produce a secondary waste stream or bond blocking dust residue on the mold surfaces. Tables 1 and 2, on the next page, present data from two mold erosion studies that were conducted by a major tire manufacturer in 1991, and again in 1996. Table 1 shows the results of the 1991 tests, where CO_2 pellet blasting was examined to see what erosion effects were apparent in four types of tire mold materials (steel, forged aluminum, and two types of cast aluminum) using three different CO_2 pellet blast nozzle configurations.

Table 1. - 1991 Tire Mold Material Erosion Rate Study Results
CO_2 Mold Cleaning Abrasion Trials 9-19-96

Material	Test Conditions	Average Change in Surface Roughness *(μm)*	Maximum Change in Surface Roughness *(μm)*	Rate of Change of Surf Rough per Clean Cycles	Average Change in Coupon Weight *(grams)*	Maximum Change in Coupon Weight *(grams)*
Steel	1	-0.82	0.2	-.036	0.01	-0.02
	2	-0.26	1.8	-.038	0.00	0.0
	3	-0.94	0.0	-.014	0.02*	-0.02
Forged Aluminum	1	0.24	1.0	-.005	0.00	0.0
	2	0.88	1.6	.022	0.02*	-0.02
	3	0.28	1.1	.001	0.02*	-0.02
Cast Aluminum A	1	2.88	5.2	.132	-1.57	-5.43
	2	-0.08	0.6	.014	-0.60	-4.02
	3	1.10	3.4	.027	-1.02	-4.55
Cast Aluminum B	1	2.30	4.0	.102	-0.93	-2.01
	2	1.90	1.9	.183	0.18*	0.18*
	3	6.85	6.85	.078	0.0	0.0

*** weight gain attributed to oxide formation and/or foreign material**

All samples were blasted with CO_2 pellets at 300 psig blast pressure. Pellet mass flow rate was 250 pounds per hour. Three different single-hose system blast nozzles were used. Negligible effects of blasting were seen on the steel and forged aluminum samples, while both cast aluminum showed minimal to severe erosion. Nozzle design had the most significant effect on erosion rate and cleaning cycle time.

The 1991 and 1996 mold erosion studies were conducted at significantly higher blast pressures (250 to 300 psig) and at higher particle velocities than required to clean typical tire and rubber molds with today's technology. This is because CO_2 pellet blasting nozzle design technology has advanced significantly from the 1991-1996 era. Nozzle and delivery system improvements now allow molded rubber products manufacturers to completely clean rubber molds at blasting pressures between 70 and 90 psig. Pellet flux density (the distribution of CO_2 particle impacts per unit area per unit time) at the mold surface is now better than it has ever been because of the aerodynamic advances in the single-hose blast delivery system. Rubber-mold specific blast nozzles now exist to focus the blast energy only where it is needed in the complex geometry of rubber mold cavities. The rubber mold fouling residue removal capability of CO_2 particle blasting is significantly better than it was only 3 or 4 years ago, at much lower air pressure and overall kinetic energy delivered to the mold surface. Presently, CO_2 particle blast induced mold erosion, even for cast aluminum molds, is considered *negligible*, and a significant number of molded rubber products manufacturers are now specifying and purchasing CO_2 particle blast mold cleaning systems to replace their existing abrasive blasting systems and methods.

Also, CO_2 particle blasting can effectively remove most imbedded grit residue left on the mold surface from abrasive cleaning methods, as well as remove grit residue from vents and microvents. This allows mold release agents to work better, and can even lead to the reduction of the amount of mold release required substantially decreasing the rate of deposit of mold fouling substances.

Table 2. - 1996 Tire Mold Material Erosion Rate Study Results
Compressed Air Usage and Cost Considerations

Sample #	Pre-Cleaning Weight (grams)	Post-Cleaning Weight (grams)	Weight Loss (grams)	Cleaning Cycle Time (minutes)	Number of Cleaning Cycles	Equivalent Cleaning Duration
1	301.64	301.54	0.10	2	18	6 months
2	304.43	304.40	0.03	2	18	6 months
3	295.85	295.78	0.07	2	36	1 year
4	302.37	302.28	0.09	2	36	1 year
5	298.71	298.62	0.09	2	72	2 years
6	298.71	298.64	0.07	2	72	2 years

For purposes of this trial, the following parameters were used:

- 10-day pull schedule
- 250 psi blasting pressure (compressed air)
- 3” x 5” engraved 2618 - T6 aluminum coupons
- 2 minute cleaning cycle
- CO2 pellets
- 360 production days
- 36 cleanings per year

NOTE: Current segmented mold cleaning cycle times are as follows:
Top sidewall: 5 min.; bottom sidewall: 6 min.; tread: 16.5 min.

Another benefit related to the low blast air pressure and volume requirements for today’s single hose CO_2 particle blasting systems is that it reduces the costs associated with the required compressed air system. Earlier, high pressure based single hose CO_2 systems required expensive, dedicated air compressors. Current single-hose direct acceleration systems use “shop air” at 70 to 80 psig and between 150 and 200 scfm. Most past and current two-hose CO_2 systems require two or more times the air flow volume, even at “low pressure”, than a state-of-the-art low pressure single hose system. In a compressed air system, high pressure and high flow volume dramatically increase operating costs in terms of equipment costs and energy (electricity) consumption. Any cost to benefit analysis for a CO_2 blast rubber mold cleaning system should include the compressed air system fixed and operating costs.

Selecting the Correct System for Rubber Mold Cleaning and Maintenance.

Direct Acceleration System vs. Inductive Systems

Kinetic and Thermal Energy Effects

Solid CO_2 particle blasting systems are available in two basic configurations. The least complex and least costly to produce is the inductive, “two-hose” system, sometimes called an *“inductive, or venturi system”*. These systems are typical of sand, PMB, and glass bead blasting systems, and most CO_2 particle blast systems available today employ this method. The blast media is sucked into a chamber in the hand held applicator, or “gun”, by the venturi effect, then propelled out of a short nozzle by a high volume flow of compressed air. Because these systems rely on the creation of a strong suction to bring the blast media from the storage hopper to the nozzle, the length of the interconnecting dual blasting hose is typically limited to fifteen feet or less. In the two hose system, one hose is the media suction hose, and can be constructed from lightweight material. The other hose is the compressed air delivery hose which, is typically heavier, to withstand pressures as high as 200 psig or greater.

In the two-hose systems, the media particles are moved from the hopper to the "gun" chamber by suction, where they drop to a very low velocity before being induced into the outflow of the nozzle by the large flow volume of compressed air. Since the blast media particles have only a short distance in which to gain momentum and accelerate to the nozzle exit (usually only 8 to 12 inches), the final particle average velocity is limited to between 200 and 400 feet per second. So, in general, two hose systems, although not as costly, are limited in their ability to deliver contaminant removal energy to the surface of a mold. When the need for more blasting energy is required, these systems must be "boosted" at the expense of much more air volume required, usually higher blast pressure required as well, with much more nozzle back thrust, and very much more blast noise generated at the nozzle exit plane.

The other type of solid CO_2 media blasting system is like the "pressurized pot" abrasive blasting system common in the sand blasting and PMB blasting industries. These systems use a single delivery hose from the hopper to the "nozzle" applicator in which both the media particles and the compressed air travel. These systems are more complex and a little more costly than the inductive two hose systems, but the advantages gained greatly outweigh the extra initial expense. In a single hose solid CO_2 particle blasting system, sometimes referred to as a *"direct acceleration"* system, the media is introduced from the hopper into a single, pre-pressurized blast hose through a sealed airlock-feeder. The particles begin their acceleration and velocity increase immediately, and continue to gain momentum as they travel the length of the hose. At the end of the hose, the spray nozzle "gun" actually consists of a convergent-divergent (isentropic flow) nozzle which, exchanges pressure differential across the nozzle for a huge increase in air and particle velocity. CO_2 particle velocities have been measured and substantiated in excess of 700 feet per second, and up to as high as 950 feet per second at the nozzle exit plane. This is accomplished at less than one third of the flow volume required by the most aggressive two hose systems.

In addition to the lighter weight and less cumbersome hand held applicator and hose of a single hose system, the contaminant removal energy delivered to the surface is considerably higher than that provided by a two hose inductive system. Even with solid CO_2 particle blasting, a significant component of the of the contaminant removal energy is the kinetic energy per unit of area delivered to the surface. Since kinetic energy is a function of mass and velocity of the particles in the relation $K_e=1/2\ mv_2$, it can be seen that a two-fold increase in particle velocity, given equal particle mass and equal nozzle spray area, effectively increases the impact energy delivered to the surface by a factor of four. A three-fold particle velocity increase, from 300 to 900 feet per second, increases the blast impact energy nine times!

Table 3 shows the relative cleaning performance between a single hose system and a two-hose system at typical "factory air" blasting pressure. The term C_{vbe} is called the Blast Energy Coefficient, and represents comparative capability of a CO_2 particle blast system to remove a volume of soft pinewood from a test specimen within a controlled interval of time.

Table 3. Comparing the Blast Energy Coefficient of Single Hose vs. Two Hose CO_2 Particle Blasting Systems

NOZZLE MODEL	NOZZLE CAPABILITY	DELIVERY SYSTEM	PRESSURE PSI	PELLETS LB/HR	TRAVERSE IN/SEC.
523 SF	High	Single Hose	80	160	0.75
508 SL	Medium	Single Hose	70	200	0.75
EA-145	High	Two-Hose	80	200	0.75

WOOD REMOVED IN**2	BLAST ENERGY Cvbe	SWATH IN.	DEPTH IN.	ENVELOPE IN.	POWER INDEX
0.37	0.278	1.2	0.11	20	3.05
0.186	0.140	0.8	0.19	11	2.65
0.135	0.101	0.8	0.11	23	1.11

As the data in **Table 3** illustrates, the typical blasting energy of a single hose system compared to a two-hose system at equal blast pressure is about three times greater.

CO_2 Blasting Media Types

Solid carbon dioxide blasting media is currently available in two forms, discrete rice grain sized *pellets* which, are produced by pressure extruding and cutting "strings" of dry ice, and sugar granule-sized *flakes* of dry ice produced by mechanically shaving the face of a large block of dry ice. To understand the differences in mold cleaning performance between the two CO_2 media forms, some technical background discussion is appropriate.

Traditional abrasive particle blasting, and even the "mildly abrasive" blasting technologies like PMB and glass bead, rely on the intrinsic surface hardness and geometry of the media, and the work available at the surface resulting from the kinetic energy of the media acting through the surface hardness and geometry.

The hard, sharp abrasive particles actually break into smaller pieces that "ricochet" into mold surface features for additional residue removal action. The total kinetic energy of abrasive media particles is therefore spread out over more than a single impact per particle. With solid CO_2 media however, the particles completely disintegrate and sublimate to CO_2 vapor upon the initial impact, so all of the solid CO_2 particles' kinetic energy are spent in one impact per particle. There is no ricochet or secondary impact effect in solid CO_2 particle blasting. Therefore, CO_2 particle blast mold cleaning performance is determined by a parameter called *flux density*. Flux density is defined as the number of particle impacts at the mold surface per unit of area per unit of time. In other words, for two CO_2 particle blasting systems with nozzles of equal exit plane area, assuming that the particles from each system possess sufficient and equivalent kinetic energy, the system that can deliver more particles to the surface in the same amount of time, or the same amount of particles in less time, will generally remove fouling residue faster and more completely.

CO_2 Particle Dynamics

As mentioned earlier, CO_2 particle blasting harnesses two types of energy to accomplish mold fouling residue removal. CO_2 particle size directly influences the level of kinetic (velocity or impact) energy and thermal (temperature gradient or thermal stress) energy available at the surface. Large pelletized CO_2 media is typically 3mm in diameter and between 5mm and 8mm in length. The sugar grain sized flake particles resulting from shaved dry ice block are roughly spherical and 0.5mm to 1mm in diameter. In the pelletized CO_2 system, by the time the pellets are accelerated and travel through the blast hose and the nozzle, they are fractured into roughly uniform sized irregular spheres of dry ice about $_2$mm in diameter. Given that the solid CO_2 is of the same density in both particles, the fractured pellet "spheres" possess about 4 times the mass of the individual shaved flakes or granules. Referring back to the kinetic energy equation, each pellet, if traveling the same velocity of each granule, delivers 4 times the impact energy at the surface. Since the fractured pellet spheres in the single hose blasting system typically travel 3 times faster than the shaved block granules in the two-hose system, the kinetic energy increases by a factor of 4 X $3^2 = 36$. This is the significant underlying factor in the ability of the high velocity, single hose CO_2 pellet blasting systems to dislodge and remove the rubber residue anchored into undercuts and corner profiles, and the vents of rubber molds.

Thermal energy is dependent upon the mass (number and size of particles) of solid CO_2 delivered to a given area of the surface per unit of time. There is a tremendous latent heat transfer as the solid CO_2 changes phase to vapor CO_2 at the mold surface (246 BTU per pound of solid CO_2). This heat exchange with each impacting CO_2 particle occurs within a few milliseconds and the heat is given up mostly from the thin layer of residue, and some from the surface of the mold. It is this instantaneous "surface only" heat transfer effect which imparts the thermal stress into the residue to fracture it from the mold surface. Having already described the particle velocity and mass delivery characteristics of the single hose, isentropic nozzle systems relative to the two hose inductive nozzle systems, it is evident that the single hose system delivers more thermal mass per unit of area per unit of time. Therefore, it produces the best thermal "shock" or residue fracturing effect. If the CO_2 blasting system cannot deliver this effect efficiently and instantaneously, and if the nozzle traverse rate over the surface is reduced to "make up" for a lower thermal mass delivery rate, the effect will be lost as the mold cross section begins to lose heat from "too much CO_2 striking it too slowly". This is typically why two-hose inductive systems fail to give rise to the thermal fracturing effect in molded rubber products mold cleaning applications. It is a matter of too little kinetic and thermal energy available in a given instant on the mold surface to be fully effective.

Table 4 shows the results of a comparison study in which mold sidewalls on both sides of a two-mold, two piece tire press were cleaned, one side with a single hose, CO_2 pellet based system, and one side with a two-hose, shaved CO_2 block system, using the same operator.

Mold Vents

Mold vents that become clogged with rubber or other fouling residue prevent the flow of trapped air or outgassing from the compound being cured to exit the mold cavities. Trapped air or other gasses in the cavities causes non-fill and flow line defects in the parts, and the defective parts must be scrapped. Keeping the vents continuously clear of rubber and fouling residue is a major concern for most rubber product manufacturers to reduce or eliminate the scrap rate. The high kinetic energy of the CO_2 particles in direct acceleration single-hose CO_2 blasting systems have proven very effective at clearing vents as small in cross sectional diameter as .030 inch. The rapid kinetic chiseling action on the residual rubber / release agent chemical residue in the vents tends to dislodge and blow out the plug of material, even while the surface of the mold is being cleaned. Even vents that are normal to the surface, like tire mold pin vents (micro vents) are readily unplugged with the CO_2 pellet blasting process.

Table 4. Comparative Results of Tire Mold Cleaning with Single Hose CO_2 Pellet Based System vs. Two-Hose, Shaved CO_2 Block System

Single Hose CO2Pellet Blasting System		Two-Hose Dry Ice Block Shaving Blast System	
Mold cavity	269	Mold cavity	270
Top half sidewall cycle	4 min. 10 sec	Top half sidewall cycle	11 min. 40 sec
Nozzle	Isentropic (low press)	Nozzle	Inductive (round)
Blasting pressure	60 psi	Blasting pressure	70 psi
Pellet feed rate	50%	CO2 block feed rate	60%
Mold cavity	269	Mold cavity	270
Bottom half sidewall cycle	4 min. 25 sec	Bottom half sidewall cycle	11 min. 0 sec
Nozzle	Isentropic (low press)	Nozzle	Inductive (round)
Blasting pressure	60 psi	Blasting pressure	85 psi
Pellet feed rate	50%	CO2 block feed rate	60%
Total cleaning cycle	**8 min. 35 sec**	**Total cleaning cycle**	**22 min. 40 sec**
Total pellet usage	**27.6 lbs.**	**Total CO2 block usage**	**44 lbs.**

Mold Cleaning Methods for CO_2 Technology

Special Nozzle Configurations

CO_2 particle blast mold cleaning is a "line of sight" process. The CO_2 high speed particles must impinge on the fouled surface at as close to 90^o as possible. Additionally, the exit, or "tip" of the blasting nozzle must be kept at 1.0 to 1.5 inches from the surface being cleaned to obtain the maximum energy from the CO_2 particles. These fundamental requirements, plus the fact that most rubber presses have 4 to 8 inch throat openings with 20 inches or more of "depth" (length of the tooling), dictate that the CO_2 high speed nozzles and the hand-held applicators must be compact, able to turn the flow of high speed CO_2 particles at angles of 90^o or greater, produce little or no nozzle backthrust, and provide the ability for the mold cleaner to see the details of the molds as he cleans them. At the same time, the nozzle design must accomplish all of this using the lowest air CFM and producing the least noise possible, without sacrificing significant blast energy delivered to the surface of the mold.

The single hose, direct acceleration method of CO_2 particle blasting provides the correct physical attributes to allow the design of high energy "flow turning" and "retro jet" rubber mold cleaning nozzles. State-of-the-art computational fluid dynamics computer modeling and design programs are used to optimize blast energy while minimizing air flow and associated noise. A high energy flow turning nozzle for a 5 or more inch press opening is illustrated below in Figure 2.

Noise Associated with Manual Blasting

Noise created by the CO_2 particle blasting equipment is another factor to be considered. All compressed gas (air) based particle-blasting technologies are inherently noisy. The power level of the noise generated at the blast nozzle exit is largely a function of the compressed air outflow volume and velocity. To a lesser extent, another component of the total noise is also created by the aerodynamic interaction of the individual CO_2 pellets or particles with the air stream. In molded rubber mold cleaning operations, the noise from the nozzle is efficiently reflected back to the operator by the flat surfaces of the mold tooling and/or the inside walls of the press. Noise, specifically the Sound Pressure Level (SPL) in decibels (dbA), is a very real concern and problem to overcome in manual CO_2 particle blasting.

Figure 2 – Cleaning a Rubber Mold with a High Energy, Flow Turning CO_2 Particle Blasting

Very significant advances have been made in the last two years to allow operators to use CO_2 particle blast to clean rubber molds in the presses, and still meet the OSHA regulations requiring less than 84 dbA SPL exposure for an eight hour period in a day. In the single hose constant acceleration system, the physics of isentropic flow have been enhanced by state-of-the art aerodynamic theory and design practice to produce media delivery systems (hose, applicator, and nozzle) which provide maximum acceleration and velocity to the particles with minimum shock or turbulence at the nozzle exit. Thus, cleaning performance is high, and generated noise is very low, typically below 102 dbA at the nozzle exit. Studies have indicated that, by using the new low-noise single hose CO_2 particle blasting systems, while the operator wears an approved blasting helmet or headphones AND state-of-the-art ear plugs (dual hearing protection), the noise (SPL) field to which the operator's ears are exposed is well below the required 84 dbA for 8 hours of continuous blasting per day.

Table 5. Noise (SPL) Generated While Cleaning Molded rubber products Mold Sidewalls with a Single Hose CO_2 Pellet Blasting System.

Trial #	Mold Code	Cycle Time (min:sec)	Threshold Setting (80 dBA)	Threshold Setting (90 dBA)	Nozzle Pressure psi	Pellet Flow Rate (%)
Segmented						
1	P225/50R16	13:53	98.08	97.61	40	55
2	P225/50R16	8:25	97.73	97.14	50	55
3	P225/60R16	7:00	97.49	97.1	60	55
4	P225/60R16	6:49	97.67	97.08	60	55
Two-Piece						
1	LT265/75R16	13:03	86.48	74.37	50	55
2	P275/60R15	8:27	95.93	96.28	55	55
3	P275/60R15	7:50	95.91	96.38	60	55

Table 5 shows the results of noise level data taken during in-the-press mold cleaning tests at major tire manufacturer in mid-1996. The data presents SPL levels measured at the operator's ear level, outside the blasting helmet resulting from blasting with a single hose system at various pressures. The noise level at the operator's ear were within OSHA standards for several hours of mold cleaning time.

Redeposition of Mold Fouling Residue

It is certainly true that the use of solid CO_2 as a surface cleaning media creates no significant secondary waste stream. Over time, however, the fouling residue "dust" which leaves the mold surfaces will redeposit on other parts of the presses and factory production area. Although redeposited residue build up may take weeks or months to even become noticeable, it is in the best interest of the rubber parts manufacturer to deal with if first hand. To date, the most effective and proven method to curtail residue redeposit is to provide adequately sized (CFM) air extraction hoods or air returns located close to the presses. The normal factory air handling system can capture most of the airborne residue particles and bring them to a central filtering station.

Emerging Rubber Mold Maintenance Technologies

Coated Molds

The most promising R & D work occurring to reduce mold fouling and parts sticking in the molds is the development of "permanent" Teflon based coatings for aluminum and steel mold surfaces which significantly minimize residue adherence and build-up. Early testing with proprietary coatings applied to production tire molds have shown that the molds can remain unfouled for more cure cycles than identical uncoated molds. When the coated molds eventually accumulate residue build-up, the fouling can typically be removed by reduced energy CO_2 particle blasting, without damaging the coating layer. Once again, with the advent of coated molds, the single hose direct acceleration CO_2 particle blast systems will offer the most benefit because these systems can utilize blast nozzles with widths up to six (6) inches wide and at the low pressure and kinetic energy level required for the coated molds. Cleaning coated rubber molds can be fast and easy at very low noise, air pressure and CO_2 pellet flow rates by employing the very wide nozzles available only with single hose systems.

Laser Mold Cleaning

Laser rubber mold cleaning technology is now available in its developmental stages. Laser technology has shown adaptability for cleaning the surfaces of passenger and light truck tire molds and other rubber product molds, even while they are in the press, but it is questionable if it is able to consistently clean deep cavities, undercuts, vent, and hard to access complex mold tooling. Many trial demonstrations and longer term tests of the laser mold cleaning technology has been accomplished in the tire industry in the last two years. In the tire industry, laser mold cleaning has been determined to be non-viable for several reasons, including personnel safety, high cost, inability to thoroughly clean the molds, inability to clean precision details within the molds, lack of industrial robustness of the equipment, and high electric power consumption. Laser technology may evolve to address these problems, but this may be years away. For now, CO_2 particle blast technology offers the best solution to productivity gains in the rubber molding industry.

Additional Uses for CO_2 Particle Blasting Technology

The very same portable CO_2 particle blasting systems which are used primarily for molded rubber mold cleaning have many other proven uses in rubber manufacturing facilities. Currently, users of this technology are applying it to the cleaning and maintenance of Banbury mixers, extruder screws and barrels, sprues, runners, gates, ejection pins, and general cleaning of the presses during downtime maintenance. When assessing existing and newly emerging molded rubber mold cleaning technologies, the possibility of applying CO2 particle blasting technology to many other areas of the rubber products manufacturing process, and the overall favorable impact to product quality and manufacturing productivity, should not be overlooked.

Summary

From the standpoint of fixed (purchasing the system equipment) and operating (electricity, compressed air, CO_2 pellet media) costs, cost-to-benefit ratio studies conducted by major molded rubber products manufacturers have proven that CO_2 particle blasting technology is currently the best choice for rubber mold cleaning.

The single hose direct acceleration solid CO_2 particle blasting system is preferred over a two hose inductive system as the most capable for maintaining rubber molds in an un-fouled condition throughout a rubber product production run. It is the high level of kinetic energy provided which is capable of removing fouling residue from deep cavities, undercuts, sharp part details, and for removing the quickly built-up residue resulting from rubber-to-metal bonded parts and excess release agent. Further, it is the thermal effect of the CO_2 media for quick removal of the glass-like fouling residue that gives the single hose system its "double punch" for quick, efficient, and complete rubber mold cleaning.

This article is based on a paper given at the September 1999 Rubber Division meeting.