BOOST PRODUCTIVITY OF PLASTIC MOLDED PRODUCTS USING DLC / DYLYN® COATINGS [1]

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A empresa de moldagem encontra vários novos desafios na moldagem de plásticos de alto desempenho : esses desafios são ligados com o preenchimento do molde, a facilidade do material soltar do molde (desmoldagem, 'release'), desgaste abrasivo, corrosão e temperaturas mais altas de moldagem. Esses fatores levam para ciclos de produção maiores, menor tempo de vida do molde, maior porcentagem de sucata e maior número de horas paradas da máquina de moldagem. Revestimentos de DLC/Dylyn® oferecem soluções para estes problemas, devido às propriedades específicas destes materiais : uma combinação de proteção contra abrasão, facilidade de desmoldagem e uma resistência a corrosão superior a outros tratamentos de superficie similares como PVD TiN ou Cromo eletrodepositado. Revestimentos em si só nunca serão uma solução completa : o desenho, a escolha do material e a preparaçao do molde antes do revestimento são fatores importantes. O aumento da produtividade obtido com os moldes revestidos de DLC/Dylyn® é o resultado de diferentes aspectos : a melhor proteçao leva a um tempo de vida maior e gastos menores com o molde ; a reduçao de resíduos plásticos e a desmoldagem mais facil reduzem as horas paradas da maquina e levam a um ciclo de produção mais rápido. Alguns exemplos são dados em vários campos para ilustrar os benefícios dos revestimentos DLC/Dylyn®

Palavras-chave: Moldes para plástico, DLC, revestimento

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INTRODUCTION:

The continuing growth of the use of plastic objects for all kinds of activities is benefiting every person, every day in areas such as work, play, home, etc. Demands made on these plastic objects vary widely from the workplace to the home. To meet these needs, the plastic industry is constantly looking at more families of plastics, better ways to strengthen plastic, making the plastic fire and fungus resistant and many other options. When these improved plastics need to be molded, many more problems are faced by the molder than ever before. The issues deal with mold fill, mold release, abrasive wear, corrosion and higher molding temperatures. All these issues are creating major headaches for the plastic molder and are leading to longer cycles, less tool life, more scrap and more downtime.

Diamond-like carbon coatings (DLC) provide many answers to the injection molder's problems due to its lower surface energy, self-lubricating behavior, high wear resistance and corrosion protecting characteristics. The purpose of this paper is to describe what DLC/Dylyn® is, define DLC/Dylyn® coating properties, contrast DLC/Dylyn® coating to common industry practices and illustrate the ways DLC/Dylyn® coating can impact plastic molding practices.

ISSUES FACING THE PLASTIC MOLDER

Plastic molding practices are influenced by several factors. Many of today's plastic molding materials contain fillers to create unique colors, strengthen them or make them flame and/or fungus resistant. These fillers can add considerable wear and corrosion concerns for the plastic mold tooling. Several families of basic plastic material such as PVC that creates chlorine and Nylon that creates nitric acid as byproducts when molded generate a corrosive environment for the plastic mold tooling.

The use of molded plastic for food or medical applications requires the molder to run without mold release agents because of contamination issues. Pressure to reduce cycle time and increase production rates along with molding without lubrication has caused the mold tool designer to use base materials with better thermal conductivity. However, many of these materials tend to be softer and more prone to corrosion and wear problems than the traditional choices.

All these factors add up to major production and tool life issues that greatly affect the molder's ability to produce plastic parts on a timely and cost efficient basis. DLC/Dylyn® coatings have properties that can reduce the effect and cost of these molding factors to the plastic molder.

WHAT IS DIAMOND-LIKE CARBON COATINGS?

Diamond-like Carbon coatings (DLC) are a family of coatings made up primarily of Carbon chains in an amorphous structure with sp^2 (trigonal) and sp^3 (tetrahedral) bondings. Sp^3 is the cubic form of carbon known as diamond compared to sp^2 that is graphite. There are different types of DLC: hydrogen-free (a-C), hydrogenated (a-C:H) or metal-doped (Me-C:H) coatings. DLC coatings present specific tribological properties: high hardness, low friction, high wear resistance and chemical inertness. The work presented here concerns hydrogenated amorphous carbon coatings. Changes to operating parameters can influence the hardness, surface energy and coefficient of friction. One variation of DLC coatings is our proprietary Dylyn® coating where Silicon/Oxygen chains are introduced into the amorphous Carbon structure: it consists of two amorphous interpenetrating networks, a diamond-like (a-

C:H) network and a glass-like (a-Si:O) network [1-2]. Dylyn® has lower hardness than DLC, but offers a lower surface energy and a lower coefficient of friction.

DEPOSITION PROCESS

DLC/Dylyn® coatings are applied by process called Plasma Assisted Chemical Vapor Deposition (PACVD). The PACVD process is done in a high vacuum chamber, in the range of 10^{-3} mbar. The plastic mold tooling is cleaned to remove all dirt, greases and oxides. The cleaned tools are attached to fixtures and then suspended from planetary plates so they can freely rotate in the coating chamber for the most uniform coating distribution during the PACVD process. The coating chamber is placed under high vacuum. Prior to deposition the tools are plasma etched. Carrier gases are introduced into the chamber, ions are formed in the plasma and are attracted by the oppositely biased tools and the film grows by chemical reactions at the surface.

Changing the gases or the deposition parameters will result is different DLC/Dylyn® coatings having differences in the hardness, chemistry, surface energy, coefficient of friction and wear resistance.

The tools do not need to be pre-heated to a special temperature in order to form the bond to promote adhesion as in other processes like Physical Vapor Deposition (PVD). However, the tools will slowly heat up to a maximum temperature of 200°C due to radiant energy. This is well below the heat treat temperatures of most plastic mold tool materials.

Another consideration for load efficiency and coating distribution is the size and complexity of the tooling. Normal coating thickness is 2 µm, but it can be applied from 0.2 to 5 µm thick depending on application needs. Although this is not a line-of-sight process, the ability to coat into deep holes or slots is influenced by the closeness of the walls. As the gases penetrate into the close areas, the attraction of the charged particles to the walls reduces the amount of ions as they travel deeper into closed areas causing a reduction in material to form the coating. Very pointed shapes or edges tend to attract more ions and coating parameters need to be adjusted to control the thickness of the coating. This effect is not anywhere as strong as observed in the electroplating processes and geometries do not need to be adjusted to compensate for the difference in growth rates.

DLC COATING PROPERTIES

DLC/Dylyn® offers a unique combination of properties not available in any other single surface treatment. Possessing a low coefficient of friction and a low surface energy approaching that of Teflon®, but with a hardness greater than carbide or Titanium Nitride (TiN), DLC/Dylyn® offer a unique wear and release combination.

The plastic additives, to increase plastic toughness, resist mildew, add fire resistance and offer many colors, can create a highly abrasive melt that aggressively wears the mold material during injection and/or release of the plastic parts. Referring to Table # 1, the DLC/Dylyn® offer a hardness range from 10 to 25 GPa that significantly increases the surface wear resistance of all plastic mold tool materials. But the DLC/Dylyn® coating surface hardness will not change the substrate materials ability to support a load: under high loading conditions, a hard tool material is necessary to support the DLC/Dylyn® coating to offer the wear resistance [3].

Many of the plastics used today are very sticky and the effectiveness of plastic part release has a very direct impact on productivity [4]. Referring to Table # 1, the DLC/Dylyn® offer a coefficient of friction (as measured against steel) ranges from

0.05 to 0.1 (compared to 0.7 for steel) and a surface energy ranges from 25 to 35 mN/m (18 mN/M for Teflon®). So DLC coatings offer some very attractive properties to promote better release of plastic parts. However, there are many other factors that could influence release and looking at the surface energy and coefficient of friction only may not always give the expected properties.

The structure of DLC/Dylyn® is amorphous and would be similar to glass. These coatings are very dense and exhibit very little porosity thereby offering excellent corrosion protection. Since the carbon based coatings are extremely chemically stable, strong acids or bases have little or no effect. Dylyn® coated parts were compared to nickel boron and PVD TiN surface treatments in a 168 hours continuous salt spray test per ASTM B 117-97 parameters (See figure 1). The results were quite starling showing a dramatic improvement of corrosion resistance by Dylyn®.

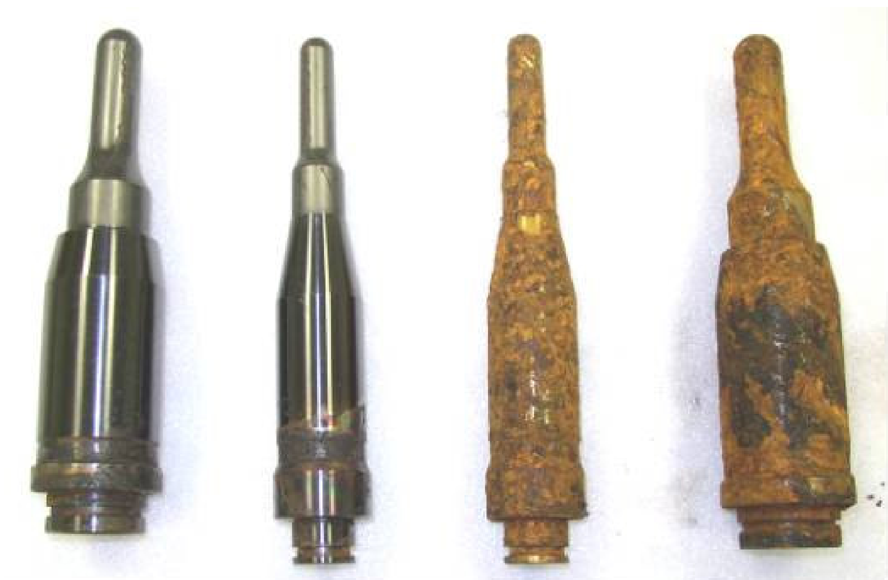

Figure 1: Salt spray tested PET cores after 168 hours

HOW DLC COATING COMPARES TO COMMON INDUSTRY PRACTICES?

The protection of the molding tooling has been an ongoing concern to the plastic molder. Surface treatments ranging from nitriding, plating processes for hard chrome and electrolysis Nickel-Teflon® composites and PVD coatings like TiN and Chromium Nitride (CrN) have been commonly used to try to protect the mold tooling from wear and corrosion as well as to improve mold release.

Nitriding [5] is a process where nitrogen is introduced into the surface of a solid ferrous alloy at a temperature below red hotness creating a case hardened to a depth of a few thousands of an inch. That gives a high hardness (70 – 72 Rockwell C), improved wear and galling resistance and improved corrosion resistance.

Physical Vapor Deposition (PVD) is performed under a vacuum system (10^{-3} mbar) where metal vapors are created by evaporation by ion beam, arc or sputtering. These vapors are generated in the form of metal ions, electrons and neutrals. Gases can be introduced into the chamber to make compounds. The ions are attracted to the oppositely charge and pre-heated (ranging between 250°C to 500°C) parts and react to form crystalline grains that grow perpendicular to the surface. PVD coating are deposited in a line-of-sight condition with the parts needing to be electrically conductive and able to withstand the coating temperature to be a good candidate for this process. PVD coating offer excellent hardness and chemical stability for good wear and release.

The Plating process [6] involves the part to be coated being placed in a metal containing chemical bath and passing current through the bath to create metal ions. The part has an opposite charge and draws the ions to the surface forming a metal coating. Complex geometries and sharp corner pose a thickness problem due to electrical field effects. The plated surface offers good corrosion resistance and improved wear. One problem is the once the plating is worn through it tends to peel back from the edge.

COATING MATERIAL	DLC	Dylyn® DLN	TiN	CrN	Chrome	Nickel Teflon	B_4C
NAME	DIAMOND LIKE COATING	DIAMOND – LIKE NANO-COMPOSITE COATING	TITANIUM NITRIDE	CHROME NITRIDE	Electroplated CHROME	Electroless Nickel Teflon® composite	BORON CARBIDE
MICROHARDNESS (GPa)	18 - 26	8 - 19	23	17	8 - 12	4 - 5	30 - 35
COEFFICIENT OF FRICTION AGAINST STEEL (DRY)	0.1 - 0.2	0.05 - 0.1	0.4 - 0.5	0.4 - 0.5	0.2 - 0.4	0.1 - 0.2	0.08 - 0.12
COATING THICKNESS (µm)	0.5 - 4	0.2 - 6	1 - 4	1 - 4	Up to 50	5 - 50	2
MAX. WORKING TEMPERATURE	570 °F 300 °C	750 °F 400 °C	1000 °F 600 °C	1300 °F 700 °C	600 °F 325 °C	600 °F 325 °C	1300 °F 700 °C
COATING TEMPERATURE	300 - 440 °F 150 - 200 °C	300 - 440 °F 150 - 200 °C	500 - 950 °F 260 - 500 °C	500 - 950 °F 260 - 500 °C	120 - 175 °F 50 - 80 °C	120 – 175 °F 50 - 80 °C	500 – 950 °F 260 – 500 °C
WEAR RESISTANCE AGAINST STEEL	+++	+++	++	++	+	+	++
SURFACE ENERGY (mN/m)	40 - 50	25 - 40	40 - 42	30 - 40		20 - 30	40 – 50
COATING METHOD	PACVD	PACVD	PVD	PVD	Galvanic Plating	Electroless Plating	PVD

Table 1: Properties of Surface Coatings

When comparing DLC/Dylyn® to PVD coatings and electroplating processes, the DLC/Dylyn® coatings have no porosity and provide excellent corrosion protection for the molding surfaces. DLC/Dylyn® coating's reduced porosity and chemically inert property extends the useful life of the mold by dramatically slowing the negative affects of corrosive plastic mold materials like PVC (Hydrochloric Acid) and Nylon (Nitric Acid) on the tooling. Another corrosive attack of the steel mold tooling comes from the presence of surface condensation created by constant heating and cooling the mold tooling during normal cycling. This corrosive action is dramatically reduced by the properties DLC/Dylyn® coatings possess.

The improved characteristic of the DLC/Dylyn® coating allows less frequent mold cleaning with a faster and easier clean up shortening the time needed to put the mold back into service. The DLC/Dylyn® coating creates more molding time and thereby adds to production efficiency and bottom line profitability for the plastic molder.

The wide variety of plastic fillers that are used create a highly abrasive plastic melt, that coupled with increasing injection pressures to decrease cycle time, create a very aggressive attack of the mold tooling surface causing fast wear. Many times the choice of tool material is based on cycle time and the tool material can be relatively short. The use of metal based plating and PVD coatings can do a good job of protecting the surface, but do not always offer protection from other molding problems. DLC/Dylyn® offer great surface wear resistance as well as bringing protection for these other molding problems.

One of the most costly issues facing the molder is the reduction of cycle time. The best way is to transfer the heat from the plastic. However, the choice of mold tool materials that can offer the best heat transference may not be used due to corrosion or wear issues. The next best solution is to coat the tooling to improve mold release. Nickel Teflon® composites and PVD coatings have been used in the past to prevent sticking. Referring to figure 2, the PVD processes create a much rougher texture that does not always provide the release the molder wants. The Nickel-Teflon® composites give excellence release, but do not have the staying power and durability to give the molder the consistency of release over the life of the mold tooling. DLC/Dylyn® provide a lower surface energy and a lower coefficient of friction that help promote better release by reducing the force necessary to eject the molded part and allow the plastic part to be hotter when ejected. One word of caution before just using DLC/Dylyn® coatings and expecting improved release based solely on a lower surface energy and a lower coefficient of friction; factors such as tool surface finish, injection temperature and family of plastics being molded may have a pronounce affect on release and should be reviewed prior to choosing any surface treatment including DLC/Dylyn® coatings.

PACVD DLC (~5000 X) | **PVD Ion/Sputter Beam TiN (1000 X)** | **PVD Arc Evaporation TiN (1000 X)**

Figure 2: SEM pictures of coatings surface

WHAT TOOL MATERIALS CAN BE COATED?

The choice of mold tool material is very critical for optimum life and mold cycle performance. To decrease mold cycle times, highly thermally conductive materials like H-13 carbon steel, aluminum and beryllium copper are used. To improve wear, materials like D-2 and A-2 hardened steels are used. To improve corrosion resistance, materials like 300 and 400 series stainless steels are used. DLC/Dylyn® can be applied to all these tool materials because of the low coating temperature and the ability to adhere well to all these tool materials. Many other surface treatment processes involve chemistries or temperatures that can have an adverse effect of the tool materials causing corrosion, hardness changes or alter the size of the tool. In addition, DLC/Dylyn® can be stripped from all these materials with very little or no changes in the surface finish by controlled etching process which does not involve any chemicals to remove the coating. As far as we know we are the only ones today, who are able to remove their carbon-coating in this considerate way.

HOW TO PREPARE MOLD TOOLING FOR DLC/DYLYN® COATING?

Due to the increasing complexity of the molded plastic shapes, most tool manufacturers employ wire or sinker style EDM (Electrostatic Discharge Machining) to produce the intricate mold tooling. The EDM process uses an electrical current to breakdown the surface in a controlled fashion generating molten drops of steel that are washed away by the electrolyte. When the current flow is stopped, these droplets converge on the surface and re-solidify forming a fractured and over-tempered zone. This zone has very poor adhesion to the base material and although DLC/Dylyn® will adhere to this zone, it could flake off during the molding operation taking the DLC/Dylyn® coating with it and exposing the base tool material. The most common practice is to finish up with a few lighter current trim cuts reducing the recast zone and this practice coupled with light pressure glass beading usually gives an acceptable surface for DLC/Dylyn® to adhere well to and perform better.

Other prior surface treatment to the surface can cause adhesion problems for DLC/Dylyn® coating. If the tool was nitrated prior to DLC/Dylyn® coating, there usually is a white layer generated depending on the process used that DLC/Dylyn® coating would stick to but would have no holding strength under load and would flake off taking the DLC/Dylyn® coating with it. On the other hand, after the thorough removal of the white layer this nitrated and extra hardened base material gives a better support function to every kind of coating. If the part is plated, the adhesion of the plated surface will influence how well the DLC/Dylyn® coating will stay in place. Once wear breaks into the tool material, the plated surface will peel and lift off the DLC/Dylyn® coating. Normally, DLC/Dylyn® coating does not peel or flake even at the edge were it has been worn through. Even with the higher adhesion of PVD coated surfaces, the DLC/Dylyn® coating conforms to the surface texture and roughness created by the PVD process. In general 'metal white' surfaces are preferred for the best and most consistent results with DLC/Dylyn® coatings.

PLASTIC INDUSTRY APPLICATIONS

The first application area DLC/Dylyn® coatings have shown to be quite effective is in area of blow mold tooling. The most effective use comes from coating all components, base, top, bottom, inserts, grips and pushups. There were two major benefits. First, the formation of plastic residue due to outgassing of the polycarbonate preform is slowed down dramatically by the presence of the DLC/Dylyn® coating. Secondly, blow molders have found the frequency of cleaning has gone from once a day to scheduled weekly mold cleaning with at least a 50% reduction in the time to clean. The net result is improved overall cycle time and more containers being produced during the same time frame.

The injection molding of polycarbonate plastic at 525° F to make preform PET cores is another DLC/Dylyn® coating application. The factor controlling cycle time is the ability of the polycarbonate PET cores to solidify enough to be ejected without deforming. The design of the tooling requires a core made of 420 stainless steel or H-13 steel with little or no draft over a few inches. The industry started to work on reducing cycle time by first trying to improve the core finish to a #1 finish, but later introduced controlled texturing by draw stoning or glass beading for best release. They also looked at common surface treatments like nickel boron and TiN, which did have a positive impact on release, but did not give corrosion protection from mold sweating they had hoped for. When DLC/Dylyn® coating where implemented, the molder observed up to a 10% faster cycle time, less maintenance downtime and longer tool life. One particular customer reported faster cycle times lasting well over a year with once a week carbon dioxide cleaning and monthly class 2 cleaning producing well over 1 million preforms.

The extrusion of white PVC plastics for furniture and electrical application is another DLC/Dylyn® coating application. The white color in PVC products is generally created by adding TiO_2 to the PVC melt and the highly abrasive TiO_2 filler acts like a liquid hone causing severe wear to the 420 stainless steel mold tooling. Another issue is PVC plastic gives off chlorine during the molding process that forms HCl acid and corrosively attacks the steel, so changing to harder more wear resistance steel is not possible. The DLC/Dylyn® coating brought both wear and corrosion resistance to the extruded.

One unexpected, but highly beneficial effect of the DLC/Dylyn® coated tooling was a self-cleaning action caused by the low surface energy in combination with the amorphous structure of the coating. One of the most plaguing problems is the burning and streaking of the PVC after idle time. Plastic residue builds ups in the tooling and while the extrusion process is idle begins to burn. When the extrusion process begins, the burnt material is transferred to the extruded product causing rejection of material for quality reasons and/or the need to pull the tooling out for complete cleaning. Andres et al. [7] showed the presence of plastic residue build up by observing the characteristics of die lines. Although after some running both Dylyn® coated and uncoated showed die lines, the Dylyn® coating reached a steady state condition for the size and density of die lines due to a self-cleaning action whereas the uncoated the size and density of die lines constantly increased until cleaning was necessary to produce good parts. The low surface energy and the pinhole free structure of Dylyn® coating prevented the build up of plastic material to a point where the burnt material could break off and cause streaking of the extrusion.

The injection molding of rubber products for the automotive market has primary issues like sticking and wear. They had tried TiN coating that had worked very well to improve release, but when they had to be cleaned in a caustic wash (HCl based solution) the TiN was removed. One customer had DLC coat some tools they tested by placing them in their caustics wash. They left the tools in the caustic wash for 5 weeks and saw no change at all in the surface of the DLC tooling. The first DLC coated mold was able to run the first day with no mold release and no change in the cycle time. However, the tool is still running over a half of year by using only 10% of the amount of mold release agent they had in the past.

In the production of closure plastic products, the molder uses unscrewing thread-cores for parts like seal caps. After production the seal caps have to be decoratively galvanized and the presence of lubricants are not allowed because they interfere with the galvanizing process. The molding the seal caps without lubrication creates a big flashing and wear problem. This customer tested quite a few other surface treatments and found the DLC/Dylyn® to be the best solution for most efficient production.

One of the best applications, but many times overlooked, is the problem of sliding parts in the mold tooling hanging up and causing unplanned downtime due to flashing, plastic particles and dirt. Many times these sliding mold parts are never even in contact with the plastic melt, but the outgassing of the melted plastic leads to thickening of the lubricant, as consequence the increase of the deforming force. DLC/Dylyn® coatings reduce wear that causes flashing and with an increased hardness in combination with an extreme low coefficient of friction, reduces the effect of dirt in the sliding mold tooling. The resulting increased uptime will reduce the average cost per molded part and increase the bottom line profitability for the plastic molder.

CONCLUSION:

DLC/Dylyn® coatings provide a combination of wear protection, improved release and corrosion resistance for the plastic molder that is unique compared to many other surface treatments. Many other processes offer excellent improvement in single areas, but often cannot offer help for all the other issues the molder is facing.

Eject-needles, columns, slide parts,… they all are mostly not expensive themselves, the advantages are mainly not linked to the protection of the tools, but well in the resulting increased productivity.

Coatings alone will never be the complete answer. Issues like release are affected by draft angles, surface finish and the direction of polish as well as the family of plastics being molded, but DLC/Dylyn® coatings can allow the designer to push the current limits. Certain problems can be corrected by use of DLC/Dylyn® coating on the existing tooling thus saving the expense of redesigning and manufacturing corrected mold tool design and increasing up time.

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BOOST PRODUCTIVITY OF PLASTIC MOLDED PRODUCTS USING DLC/DYLYN® COATINGS [(1)]

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The molder is facing new challenges when molding improved plastics: the issues deal with mold fill, mold release, abrasive wear, corrosion and higher molding temperatures and are leading to longer cycles, less tool life, more scrap and more downtime. DLC/Dylyn® coatings provide many answers due to their particular properties: a combination of wear protection, improved release and corrosion resistance that is unique compared to many other surface treatments like PVD TiN or electroplated chrome. Coatings alone will never be the complete answer: the design of the mold, the choice of the tool materials and the preparation of the mold prior to the coating are also important. The higher productivity achieved by DLC/Dylyn® coated molds results from different aspects: the better tool protection leads to higher lifetime and lower tool cost; the reduction of plastic residues and the improved release allow less machine downtime and faster cycle time. Some examples in the field of blow mold tooling, injection molding and extrusion show the benefit of DLC/Dylyn® coatings.

Keywords : Diamond-like carbon; plastic molded products

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