

Thesis
On
**MODELING, ANALYSIS, EVALUATION AND
EXPERIMENTAL INVESTIGATION OF ABRASIVE BLASTING
PROCESS**

Submitted in partial fulfillment of the requirement for the award of the degree of
Master of Engineering
IN
PRODUCTION & INDUSTRIAL ENGINEERING



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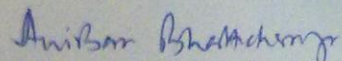
DECLARATION

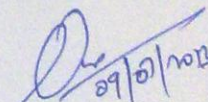
I hereby declare that the thesis entitled "MODELING, ANALYSIS, EVALUATION AND EXPERIMENTAL INVESTIGATION OF ABRASIVE BLASTING PROCESS" is a authentic record of my study carried out as requirements for the award of the degree of **Master of Engineering in Production and Industrial Engineering** at **Thapar University, Patiala**, under the guidance of **Dr. V.K Singla**, Associate Professor, Department of Mechanical Engineering, Thapar University, Patiala and **Anirban Bhattacharya**, Assistant Professor, Department of Mechanical Engineering, Thapar University during July 2012 to July 2013. The matter embodied in this thesis report has not been submitted in part or full to any other university or institute for award of any degree.

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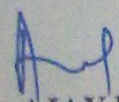
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ABSTRACT

Abrasive blasting is the operation widely used to smooth a rough surface, roughen a smooth surface, shape a surface, or remove surface contaminants. The effect of shot blasting treatment using steel shot balls on the surface characteristics of four different metals has been studied in this thesis work. Mainly focusing on output response parameters like Percentage weight loss, surface roughness, micro hardness and surface characteristics, a comparison study of Abrasive blasting using different blasting times is made. Graph theory is applied to the Abrasive blasting system for structural modeling, characterization and integrative analysis of Abrasive blasting system. System permanent function is developed which can be used to find numerical index of an Abrasive blasting system by substituting the numerical values of subsystems and their interactions.

ABBREVIATIONS

ABS	Abrasive blasting System
ML	Mass Loss
SR	Surface Roughness
MH	Micro-Hardness
RC	Relaxation Circuit
GF	Graph Theory

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CHAPTER 1

INTRODUCTION

1.1 ABRASIVE BLASTING

It is the operation of forcibly propelling a stream of abrasive material against a surface under high pressure to smooth a rough surface, roughen a smooth surface, shape a surface, or remove surface contaminants. A pressurized fluid, typically air, or a centrifugal wheel is used to propel the media. The several variants of the process are Shot blasting, Wet blasting, Sandblasting, Hydro blasting, Soda blasting, Bead blasting, Dry ice blasting, Bristle blasting, Micro abrasive blasting, Dry ice blasting etc.

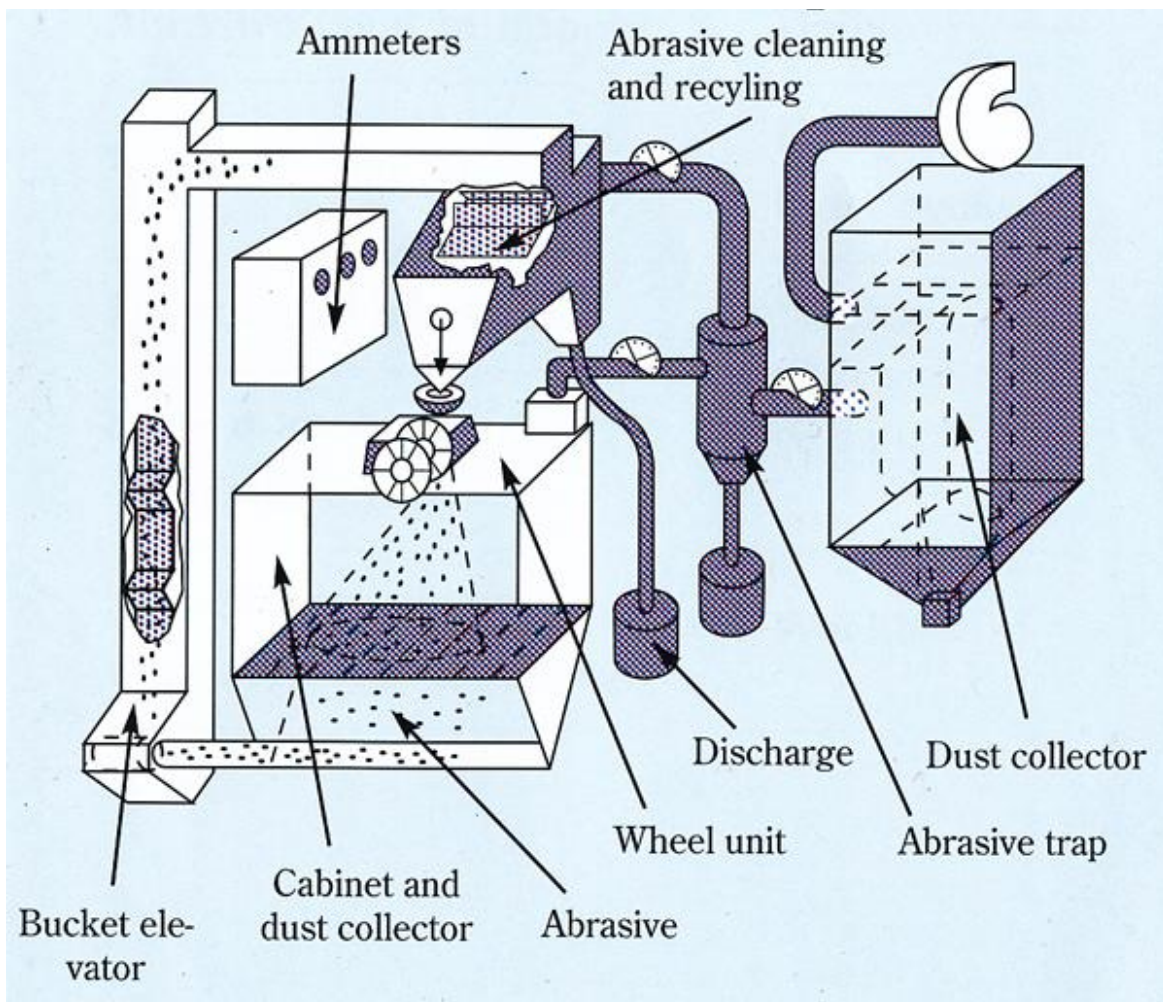


Fig. 1.1 Wheel type shot blasting

(<http://www.granowski.com.au/Equipment/Typical-Wheel-Blast-Operation.aspx>)

1. The lettering and engraving on most modern cemetery monuments and markers is created by abrasive blasting.
2. Grit blasting is also undertaken to prepare a surface before dip coating the same, using light metal alloys like Babbitt. It is also a routine procedure for cleaning the surface of a green sand molded product. The roughness obtained is dependent on the grit blasting parameters, e.g., blasting pressure, angle, standoff distance, grit size and type, etc. Micro-blasting on PVD films has been documented as a potentially efficient method for improving the cutting performance of coated tools. This process induces residual compressive stresses into the film structure, thus increasing the coating hardness, but its brittleness too [Naidu and Raman 2005].
3. Sandblasting can be used to refurbish buildings or create works of art (carved or frosted glass). Modern masks and resists facilitate this process, producing accurate results. Sandblasting techniques are used for cleaning boat hulls, as well as brick, stone and concrete work. Sandblasting is used for cleaning industrial as well as commercial structures, but is rarely used for non-metallic work pieces. To give the fabrics the right worn look sandblasting is used. Shot blasting is used in almost every industry that uses metal, including aerospace, automotive, construction, foundry, shipbuilding, rail, and many others. There are two technologies used: wheel blasting or air blasting. Specialized wheel blast machines propel plastic abrasive in a cryogenic chamber, and are usually used for deflashing plastic and rubber components [Chander et al. 2009].
4. Micro blasting of cutting tips and tools is a very effective and reliable method of advancing the life of tools under the action of turning, milling, drilling, punching and cutting [Leong et al. 1998].
5. Shot peening is one of the best methods of inducing the compressive residual stresses. The residual surface compressive stresses reduce the possibility of a propagating fatigue crack by reducing the peak applied tensile stress. The localized plastic flow at the surface, resulting in the shot peening process, causes work hardening of the surface, general roughening of the surface along with the generation of the compressive residual stresses. All of these factors can be expected to affect both the plain fatigue (without fretting) and fretting fatigue properties of a material [Riedl et al. 2012].



Fig. 1.2 Mild Steel (99.0% Fe, 0.101%C, 0.173% Si, 0.532% Mn) work piece before and after 15 minutes of steel shot blasting)

1.1.1 Shot blasting

It consists of attacking the surface of a material with one of many types of shots. Normally this is done to remove something on the surface such as scale, but it is also done sometimes to impart a particular surface to the object being shot blasted, such as the rolls used to make a 2D finish. Shot blasting is a method used to clean, strengthen (peen) or polish metal. The shot can be sand, small steel balls of various diameters, granules of silicon carbide, etc. The device that throws the shot is either a large air gun or spinning paddles which hurl the s Wheel blasting. There are two technologies used: wheel blasting or air blasting. Wheel blasting directly converts electric motor energy into kinetic abrasive energy by rotating a turbine wheel. The capacity of each wheel goes from approximately 60 kg per minute up to 1200kg/min. With these large amounts of accelerated

abrasive, wheel blast machines are used where big parts or large areas of parts have to be derusted, descaled, deburred, desanded or cleaned in some form. Often the method of transportation of the components to be blasted will define the type of machine: from simple table machines to integrated, fully automatic manipulator machines for full series automotive manufacturers, through to roller conveyors and strip descaling systems.

Air blasting machines can take the form of a blast room or a blast cabinet, the blast media is pneumatically accelerated by compressed air and projected by nozzles onto the component.

In air and wet blasting the blast nozzles can be installed in fixed positions or can be operated manually or by automatic nozzle manipulators or robots. The blasting task determines the choice of the abrasive media; in most cases any type of dry or free running abrasive media can be used. Hot off their blades. Grit blasting is a process in which angular shaped metallic or ceramic grits are carried by a pressurized air stream and hurled against the surface of the work material. The sharp grits erode the surface and a rough surface suitable for thermal spraying is created. Some of the common grits are alumina grits, silicon carbide grits, chilled iron grits, etc.

1.1.2 Bead blasting

It is the process of removing surface deposits by applying fine glass beads at a high pressure without damaging the surface. It is used to clean calcium deposits from pool tiles or any other surfaces, and removes embedded fungus and brighten grout color. It is also used in auto body work to remove paint.

1.1.3 Micro-abrasive blasting

It is dry abrasive blasting process that uses small nozzles (typically 0.25 mm to 1.5 mm diameter) to deliver a fine stream of abrasive accurately to a small part or a small area on a larger part. Generally the area to be blasted is from about 1 mm² to only a few cm² at most. Also known as pencil blasting, the fine jet of abrasive is accurate enough to write directly on glass and delicate enough to cut a pattern in an eggshell. The abrasive media particle sizes range from 10 micrometers up to about 150 micrometers. Higher pressures are often required. The most common micro-abrasive blasting systems are commercial bench-mounted units consisting of a power supply and mixer; exhaust hood, nozzle and gas supply. The nozzle can be hand-held or fixture mounted for automatic operation. Either the nozzle or part can be moved in automatic

operation. Micro-blasting is a finishing procedure based on an impact treatment of the surfaces. Generally, this procedure is applied to coatings to clean, smooth the surface and reduce sharp cutting edges. This process involves the use of high pressure and abrasive powders. Besides, there is still the possibility of achieving an attractive side effect, namely, the introduction of beneficial compressive residual stresses [Barbatti et al. 2009].

1.1.4 Dry ice blasting

In this process blasting of air and dry ice are used and with the help of a huge mass and air pressure the parent material is cleaned without destroying the properties of the parent material. The sandblasting is principally done by impacting the sand particles onto the surface of specimen by means of pressurized air flow. The type, size and geometry of the particles are among the important factors determining the result of this treatment. The recent studies utilize silica Al_2O_3 and ZrO_2 particles for the treatment. However, the possibility of using other particles for this treatment is still open.

1.1.5 Grit blasting

Grit blasting is a process in which angular shaped metallic or ceramic grits are carried by a pressurized air stream and hurled against the surface of the work material. The sharp grits erode the surface and a rough surface suitable for thermal spraying is created. Some of the common grits are alumina grits, silicon carbide grits, chilled iron grits, etc. It is necessary to make the substrate rough before thermal spraying so that the coating can stick to the substrate by mechanical anchorage [Chander et al. 2009]. This treatment has been used for many years in the processing of biomaterials and biomedical implants. This treatment utilizes multiple impacts of blasting particles to enhance surface roughness as well as the biocompatibility of metallic materials. The previous studies demonstrate better cell attachment, proliferation and development on such a rough blasted surface. Besides the roughness, the appropriate surface chemistry is required to improve the implant integration with bone tissue. The use of blasting particles with bioactive chemical elements is therefore introduced as well to produce a surface with the desired surface chemistry. The grit blasting treatment also improves the mechanical properties of metallic components. The surface severe plastic deformation that occurs by grit blasting treatment enhances the surface and subsurface hardness thanks to the formation of nano

crystallites, residual stress and martensites at these layers. Hence, this treatment is often chosen for improving the load bearing performance of metallic components [Arifvianto et al. 2012].

1.1.6 Sand blasting

It is an old abrasive machining process, and is widely used for surface treatment such as: surface strengthening, surface modification, surface clearing and rust removal, etc. In the sand blasting process, a high velocity jet of fine abrasive particles and carrier gas coming out from a nozzle impinges on the target surface and erodes it. The fine particles are accelerated by the gas stream commonly compressed air at a few times atmospheric pressure. The particles are directed towards surfaces need to be treated. As the particles impact the surface, they cause a small fracture and the gas stream carries both the abrasive particles and the fractured particles away. The important process parameters of sand blasting are the nozzle material and its geometry the jet velocity and impact angle, the erodent abrasive properties, etc. Commonly used abrasives in sand blasting are alumina, silicon carbide, glass beads, and dolomite, etc [Deng et al. 2006].

1.1.7 Wet abrasive blasting

It includes features like the ability to use extremely fine or coarse media with densities ranging from plastic to steel, the ability to use hot water and soap to allow simultaneous degreasing and blasting, elimination of dust, so silicacious materials can be used without worry, hazardous material or waste can be removed without danger like removal of asbestos, radioactive, or other poisonous products from components and structures leading to effective decontamination. The process is available in all conventional formats including hand cabinets, walk-in booths and automated production machinery and total loss portable blasting units. Process speeds can be as fast as conventional dry sand blasting when using the equivalent size and type of media. However the presence of water between the media and the substrate being processed creates a lubricating cushion that can protect both the media and the surface from excess damage. This has the dual advantage of lowering media breakdown rates and preventing impregnation of foreign materials into the surface. Hence surfaces after wet blasting are extremely clean, there is no embedded secondary contamination from the media or from previous blasting processes, and there is no static cling of dust to the blasted surface. Subsequent coating or bonding operations are always better after wet blasting than dry blasting because of the cleanliness levels achieved.

The lack of surface recontamination also allows the use of single equipment for multiple blasting operations. Stainless steel and carbon (mild) steel items can be processed in the same equipment with the same media without problems. Hydro-blasting, commonly known as water blasting, is commonly used because it usually requires only one operator. In hydro-blasting, a highly pressured stream of water is used to remove old paint, chemicals, or buildup without damaging the original surface. This method is ideal for cleaning internal and external surfaces because the operator is generally able to send the stream of water into places that are difficult to reach using other methods. Another benefit of hydro-blasting is the ability to recapture and reuse the water, reducing waste and the impact on the environment.

1.2 EQUIPMENT

A tumbling-blast machine consists of an enclosed, endless conveyor belt, a centrifugal blast wheel and an abrasive recycling system. These machines simultaneously tumble and blast the work pieces. As the conveyor moves, it gently tumbles the work and exposes all work piece surfaces to the abrasive system. Tumbblast machines can be integrated into automatic systems for high production rates. An example is the presort and tote box loader work handling system.

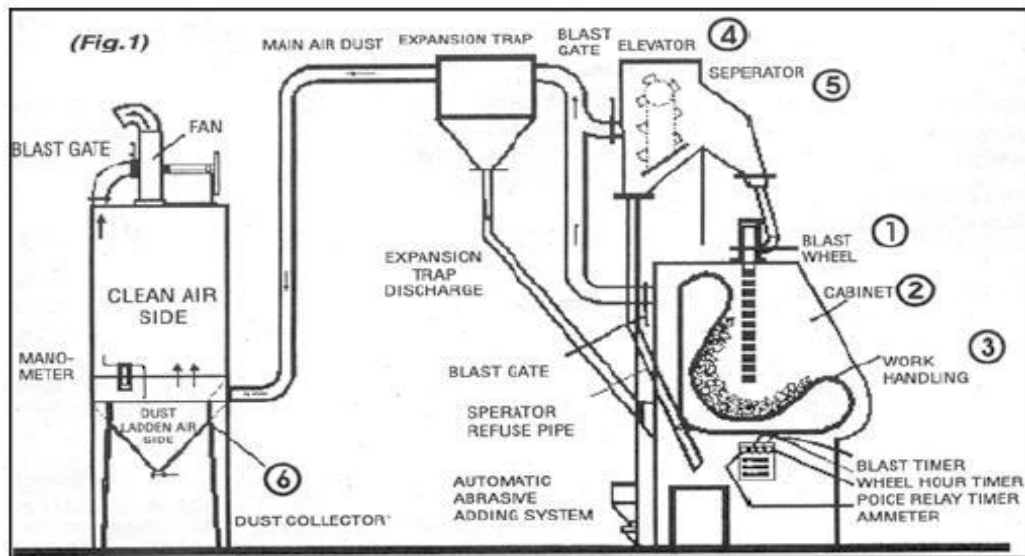


Fig. 1.3 Airless shot blasting operation

(<http://www.shot-blasting-machines.com/shot-blasting-machine.php>)

1.2.1 Blast Wheel

The airless blast wheel is the "heart" of the shot blast system. These centrifugal "airless" wheels have an internal impeller and blade design which "slings" the shot at the parts. The blast wheel acts much like a pump. The blast wheel impeller and blades are revolving at 3600 RPM's and propel the steel shot from 250 to 300 ft. per second.

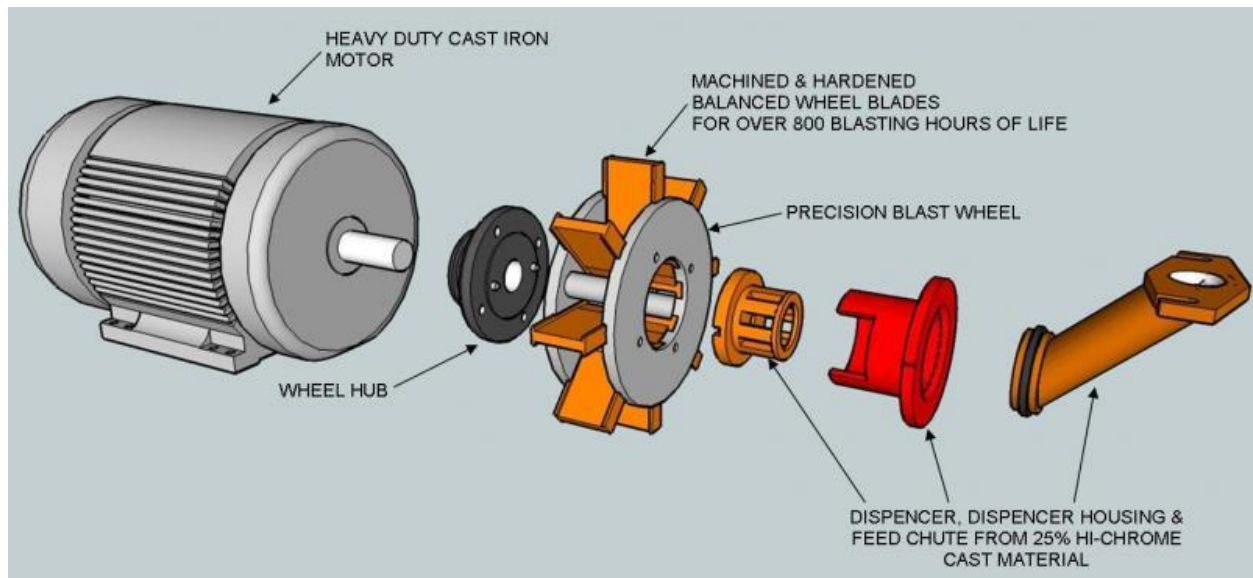


Fig. 1.4 Shot Blasting Wheel

(http://stelexinternational.net/shot_blasting_machines)

1.2.2 Blast Cabinet

The blast cabinet is the "body" of the shot blast system. The blast cabinet performs two purposes; one is to support the wheels and second to contain the steel shot within a confined area and recover it back to the primary storage hopper. The cabinet is usually fabricated from manganese steel and AR plate. The blast cabinet must withstand years of heavy duty wear in a three shift, 24 hour a day capacity.

1.2.3 Abrasive Recovering System

The abrasive recovering system is the "circulatory system" of the machine. After the steel shot is thrown from the blast wheel and strikes the parts, it falls to the bottom of the machine and is recovered via a screw conveyor and bucket elevator system. The reclaim of the media is then transported over an "air-wash" separation system to remove any small broken down

contaminants and excessive dust. The recovery system is engineered to handle the continuous recycling of 500 to 4,000 pounds of shot per minute (respectively).

1.2.4 Work Handling System

The work handling system is the "legs and arms" of the system. The work handling system is the part of the machine that presents the work to be cleaned (tumble barrel, rotating table, spinner hanger fixture, etc.); other work handling systems include: overhead monorail 1, roll conveyer, continuous mesh belt, etc.

1.2.5 Dust Collector & Air wash Separator

The dust collector & air-wash separator are the "lungs" of the machine. The dust collector provides the necessary ventilation to remove dust from the blast cabinet. It also provides an air stream across the "air-wash" separator to clean the small fines and foreign contaminants from the shot before its reused. All shot blast machines require good dust collection and air-wash separators for reliable & efficient long term operation.

1.2.6 Electrical Controls

The electrical system is the "brains" of the shot blast system. The electrical system is usually is wired for 230/460 power and controls the random start/stop operation of the machine and dust collector. The GOFF systems can also be designed and engineered with PLC automation & robotic interfacing. These automation systems usually require factory pre-programming and customer input.

1.2.7 Machine Set-Up All shot blast machines require proper set-up. The blast pattern is the most important aspect of the machine set-up. The pattern needs to be directed at the parts and not the cabinet. The blast pattern setting concentrates the blast directly at the parts and is called the "Hot Spot". The position of the "Hot Spot" is critical for maximum coverage and minimal cleaning times.

1.2.8 Machine Maintenance

The blast wheel is the most important facet to maintain on a shot blast system. It is the "heart" of the unit. The blast wheel parts are the "work horses" of the system and need to be replaced most often. The fluctuations in part life is directly related to the type of cleaning application (foundry castings, forgings, heat treated gears, etc.) and Rockwell hardness (Rc) of the shot/grit utilized.

1.3 CONSUMABLES (ABRASIVES)

1. **Mineral:** Silica sand can be used as a type of mineral abrasive. It tends to break up quickly, creating large quantities of dust, exposing the operator to the potential development of silicosis, a debilitating lung disease. To counter this hazard, silica sand for blasting is often coated with resins to control the dust. Using silica as an abrasive is not allowed in Germany, Britain, Sweden or Belgium for this reason. Another common mineral abrasive is garnet. Garnet is more expensive than silica sand, but if used correctly, will offer equivalent production rates while producing less dust and no safety hazards from ingesting the dust. Magnesium sulphate is often used as an alternative to baking soda.



Fig. 1.5 Silica Sand

(<http://www.rudraminerals.com/silica-sand.htm>)

2. **Agricultural:** Typically, crushed nut shells or fruit kernels. These soft abrasives are used to avoid damaging the underlying material such when cleaning brick or stone, removing graffiti, or the removal of coatings from printed circuit boards being repaired.

3. **Synthetic:** This category includes corn/wheat starch, sodium bicarbonate, and dry ice. These "soft" abrasives are also used to avoid damaging the underlying material such when cleaning brick or stone, removing graffiti, or the removal of coatings from printed circuit boards being repaired. Soda blasting uses baking soda (sodium bicarbonate) which is extremely friable, the micro fragmentation on impact exploding away surface materials without damage to the substrate. Additional synthetic abrasives include process byproducts (e.g., copper slag, nickel slag and coal slag), engineered abrasives (e.g., aluminum oxide, silicon carbide aka carborundum, glass beads, ceramic shot/grit) and recycled products (e.g., plastic abrasive, glass grit).
4. **Metallic:** Steel shot, steel grit, stainless steel shot, cut wire, copper shot, aluminum shot, zinc shot.



Fig. 1.6 Chilled iron grit

(<http://www.kushotblasting.com/chilled-iron-grit-933222.html> iron grit)

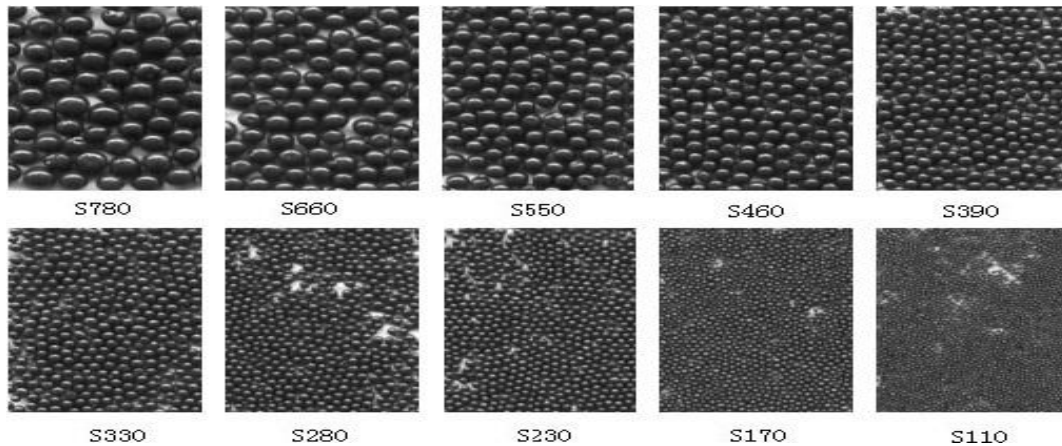


Fig. 1.7 Chilled Steel Shots

(<http://html.machsources.com/suppliers/aviva5945/products/16196.html>)

Many coarser media used in sandblasting often result in energy being given off as sparks or light on impact. The colours and size of the spark or glow varies significantly, with heavy bright orange sparks from steel shot blasting, to a faint blue glow (often invisible in sunlight or brightly lit work areas) from garnet abrasive.

CHAPTER 2

LITERATURE REVIEW

2.1 Surface Properties

Leong et al. (1998) investigated the effect of abrasive jet deburring processes on the surface finishing of jewellery models built by stereo lithography apparatus (SLA). The investigation aimed to determine the significant parameters of the deburring process, to determine a practicable range of settings of these parameters for effective deburring, and to establish the optimum settings. The parameters identified for study were the abrasive media, the nozzle distance, the air pressure and the blasting time. The result showed that the blasting time was a highly significant parameter, while the blasting distance was not. The effect of the air pressure varied with the size of the features of the .model. The effectiveness of the deburring process was also dependent on the orientation of the visible steps. In the development of an experiment strategy, statistical techniques, including factorial experiments, optimum search and *F*-Test analyses, were performed.

Yin et al. (2001) investigated the abrasive machining characteristics of a glass-infiltrated alumina used for fabrication of all-ceramic dental crowns using a high-speed dental hand piece and diamond burs with different grit sizes. The material removal rate, surface roughness, and extent of edge chipping were taken as the function of grit size. The removal rate decreased substantially with decreasing bur grit size from super coarse to fine and ultrafine). The removal rate with the super coarse burs was approximately twice that achieved with the fine burs and four times the removal rate with the ultrafine burs. The removal rate also decreased with continued machining for all grit sizes. The observed reduction in removal rate was found to be primarily due to wear of the diamond grit and accumulation of debris on the bur. A significant loss of diamond grit was observed after a long use that led to a substantial loss of cutting efficiency. It was concluded that, with respect to material removal rate and surface integrity, diamond machining was a feasible machining process for glass infiltrated alumina in the final infiltrated state.

Wakuda et al (2003) identified the material response of alumina ceramics to the abrasive particle impact in the AJM process. Three kinds of commercial abrasive particles were utilized to dimple the sintered alumina samples. The softest abrasive, aluminum oxide leads to roughening of the alumina surface but causes no engraving, due to the lack of the abrasive hardness against that of the work piece. When silicon carbide abrasive was employed, a relatively smooth face was produced, principally as a result of ductile behavior under the elevated temperature caused by the abrasive impacts. The impingement by synthetic diamond abrasive caused large-scale fragmentation and the impacted surface became rough.

Aparicio et al. (2003) determined the topographical features such as surface roughness, real surface area and the percentage of surface covered by the adhered shot particles and electrochemical behavior like open circuit potential, electrochemical impedance spectroscopy and cyclic polarization by shot blasted commercially pure Ti surfaces with different materials and sizes of shot particles. The results demonstrated that the increased surface area of the material because of the increasing surface roughness was not the only cause for differences found in the electrochemical behavior and corrosion resistance of the blasted commercially pure Ti. And those differences may be attributed to the compressive residual surface stresses induced by shot blasting. All the materials tested had an adequate corrosion and electrochemical behavior in terms of its possible use as dental implant material.

Kennedy et al. (2005) outlined the ways in which micro blasted tools, both coated and uncoated had benefited from shot blasting and resulted in greater productivity, lower cutting forces, improved surface finish of the work pieces and less machine downtime. The process of micro blasting was discussed in the paper. Its effectiveness depends on many parameters including the shot media and size, the mechanics of impact and the application of the shot via the micro shot blasting unit. Control of the process to provide repeatability and reliability in the shot blasting unit was discussed. Comparisons between treated and untreated cutting tools were made and results of tool life for these cutting tips outlined. The process had shown to be of major benefit to tool life improvement.

Deng et al. (2006) compared the erosion wear of the nozzle made by Monolithic B4C, Al₂O₃/(W,Ti)C and Al₂O₃/TiC/Mo/Ni ceramic composites caused by abrasive particle impact with dry sand blasting by determining the cumulative mass loss of the nozzles made from these materials. Results showed that the hardness of the nozzle material played an important role with respect to its erosion wear. On the nozzle entry bore section, the B4C nozzle appeared to be entirely brittle in nature with the evidence of large scale-chipping, and exhibited a brittle fracture induced removal process. The erosion mechanism of Al₂O₃/TiC/Mo/Ni nozzle appeared to be a preferential removal of the metal binder followed by pluck out of the undermined Al₂O₃ and TiC grains under the same test conditions. On the nozzle center bore zone, the B4C nozzle failed in a highly brittle manner, and there was lots of obvious micro-cracks and small pits located on this area. The primary wear mechanisms of Al₂O₃/TiC/Mo/Ni nozzle were plowing and micro-cutting by the abrasive particles.

Kameo et al. (2006) developed a new removal method for metal oxide layers formed on steel surfaces as a dry decontamination technique for radioactively contaminated metal waste. The surface oxide layers formed on metal wastes were fused with glass flux and the resulting hot glass layers were removed by thermal quenching using dry ice blasting. After optimization of operating conditions in each process, removal tests were carried out using oxidized stainless and carbon steel samples, which were prepared in boiling water reactor conditions. The experimental results indicated that the surface oxide layers were fused into the glass flux such as borax by a bead reaction and successfully removed by dry ice blasting. Energy dispersive X-ray analysis confirmed that no oxide layer remained on the oxidized steel samples after treatment by the present method.

Mohammadi et al. (2007) examined the effect of grit blasting parameters on the surface roughness of Ti-6Al-4V alloy as the substrate for plasma-sprayed hydroxyapatite (HA) coatings by using the factorial and Taguchi designs of experiments. Two grit materials (Al₂O₃ and SiO₂) each at two sizes, and two types of blasting systems (pressure and suction) were used. An equivalent surface roughness of 3.51 μm was obtained in three optimum conditions. The results of the Taguchi designed experiments were analyzed using signal to noise ratio. The tensile bonding strength of HA coatings deposited on the roughened substrates at the three different

optimum conditions was measured by the standard adhesion test. As the crystallinity of the coating at the interface, evaluated by the analysis, reduced the bonding strength of the coatings was increased. These findings suggest that the substrate surface topography significantly influences the properties of the coating at the interface.

Hui et al. (2007) prepared the conventional two-layered thermal barrier coatings (TBCs) by electron beam physical vapor deposition with ZrO_2 -8 wt% Y_2O_3 (8YSZ) as top coat and CoCrAl as bond coat on disk-shaped Ni based super-alloy and three kinds of shot peening process with different lengths of operating time were adopted for bond coating. A change took place in its surface roughness and the surface micro-hardness. A thermal cycling test at 1273 K×55 min and another at room temperature for 5 min were performed to study the effects of shot peening process on the thermal cycling lifetime of TBCs. It was found that a moderate shot peening process will be able to prolong the life time. The oxidation dynamic of the as-processed TBCs basically accords with the parabolic rule, and the oxidation test also attested to the spallation between YSZ and thermal growth oxide (TGO) responsible mainly for the failure of TBCs.

Barbatti et al. (2009) investigated the influence of micro-blasting with corundum in aqueous solution at pressures between 0.05 and 0.3 MPa was applied to CVD TiN/Ti(C,N)/ k - Al_2O_3 multilayer coatings deposited onto cemented carbides on the micro-topography, microstructure and residual stresses. The results showed that the micro blasting reduces the surface roughness and affects the coating thickness. TEM investigations revealed no significant changes on the microstructure of the k - Al_2O_3 top layer. Synchrotron X-ray investigations showed that the residual stress state of the as-deposited k - Al_2O_3 top layer was not affected by the micro-blasting treatment under the conditions investigated.

Liao and Chen (2009) provided an approach to create holes or grooves more efficiently via powder blasting process. Instead of one protective layer for mask that was conventionally used, two layers were coated on the surface of the substrate material. Such a protective coating possesses two contrary characteristics: high resistance to powder blasting and easy removal from substrate after powder erosion. Once the openings of the second layer were formed at the desired

positions via a photo-etching method, a printing method, or other methods, the holes or grooves can be obtained by etching through the openings of the second layer to the first layer and the substrate by a powder blasting process. Then the whole protective coating was easily and smoothly stripped off without any damage to the substrate by dissolving the first layer with water. Due to easy removal of the mask plus the good resistance to powder blasting and a much higher erosion rate than the one obtainable by wet and dry etching processes, the proposed process can be applied to create holes or grooves on brittle material, instead of chemical etching process, so as to achieve a good quality and superior rate of production.

Riedl et al. (2012) studied the tribological behavior of post-treated CVD α - and κ - Al_2O_3 hard coatings between room temperature and 900 C. Friction and wear correlated to the different coating surface topographies in the as deposited state and generated by metal-blasting with Al Si granulate or polishing. As a result of its higher surface roughness, the quantity of AlSi transfer material was considerably higher for α - compared to κ - Al_2O_3 . The coefficient of friction was comparable for both Al_2O_3 modification sand for all testing temperatures. Increased wear was observed for metal-blasted surfaces, especially for α - Al_2O_3 at high temperatures, which can be attributed to generation of abrasive wear debris by oxidation of the transfer material. Polishing reduced wear due to a decrease in surface roughness.

Arifvianto et al. (2012) evaluated the spherical steel slag balls obtained from the slag atomization process for use in grit blasting treatment of medical grade 316L stainless steel. The modification in subsurface micro hardness, surface characteristics (morphology, roughness, and mass loss) and chemical composition of the stainless steel after the grit blasting treatment with these particles was examined. The result showed the increasing subsurface micro hardness, surface irregularity and roughness of the stainless steel by this treatment. Surface material removal takes place as well during the blasting treatment as indicated by the mass loss of the specimen. The mechanisms of the subsurface micro hardness modification as well as those for the surface roughness and mass loss evolution during the grit blasting treatment were elucidated. It concludes that the grit blasting treatment using the steel slag balls had potential for improving mechanical properties and bioactivity of stainless steel based biomedical implants.

Arifvianto et al. (2012 b) studied the effect of steel slag ball blasting treatment on surface structure, roughness and wettability of medical grade 316LVM stainless steel. The treatment was done using steel slag balls with diameter of 2-5 mm for 1 20 min. The steel slag balls were peened onto the specimen surface using 0.7 MPa compressed air flow. The result indicated the formation of craters or defects on the blasted surface. The specimen surface roughness increased by the treatment but slightly decreased after its maximum value. The steel slag ball blasting also introduces some biocompatible elements and increases the hydrophilicity of the specimen.

Masmoudi and Khlif (2012) investigated the effect of different parameters of the blast cleaning process on properties and quality of brass parts surface. It aimed to study the following process variables: particle abrasive shape: (spherical (S) and angular (G) shot), particle abrasive size (S170, G40 and G50) and the impact velocity (40 m/s, 60 m/s and 80 m/s). An experimental approach based on three testing methods was used to quantify the analysis of particulate contaminants on substrates surfaces. These methods were: SEM, BSEM and EDXA plots from SEM imaging. The results obtained clearly show that the particle embedment decreases with decreasing of the size of angular abrasive. It was found that the angular abrasives had delivered a contamination level higher than that delivered by spherical abrasives. It was also demonstrated that the abrasive debris nature embedded in the treated surfaces was the iron. The coupling of this debris with the base metal (copper) in the presence of wetland causes an electrochemical corrosion.

2.2 Residual stress and Fatigue

Naidu and Raman (2005) described the effect of shot blasting on plain fatigue and fretting fatigue behavior of Al–Mg–Si alloy AA6061. Shot blasting significantly increased the plain fatigue life by a factor 2.8 and fretting fatigue life by a factor 2.4 at a maximum cyclic stress of 169 MPa, but at higher stress levels shot blasting slightly reduced both the plain fatigue and the fretting fatigue lives. At a maximum cyclic stress of 169 MPa, the stabilized value of coefficient of friction in the shot blasted condition was lower than that in the T6 condition (0.55 against 0.60), but at a maximum cyclic stress of 265 MPa, it was around 0.82 in the T6 condition and 0.84 in the shot blasted condition.

Chander et al. (2009) studied the effect on surface roughness and surface residual stress of low carbon steel substrates which had been grit blasted using alumina grits of various sizes under varying pressure, time, angle and standoff distances. The mechanism of material removal in grit blasting had been analyzed. The effect of blasting process parameters on substrate surface residual stress had been studied using a statistically designed experiment. The Barkhausen noise analysis (BNA) of the blasted surface had been undertaken. Then the BNA results had been calibrated against and complemented using the residual stress values measured using X-ray diffraction. The correlation between BN signal and the measured residual stress had been studied. The analysis of the experimental results shows that the surface roughness increases with grit size, blasting pressure and to an extent with blasting time and blasting angle as well. The compressive residual stress of the surface and subsurface hardness increases with blasting pressure and blasting angle. The Barkhausen noise signal had a strong correlation with the magnitude of the compressive residual stress on the blasted surface.

Bouzakis et al. (2011) investigated the effects of Al_2O_3 and ZrO_2 grains, in dry micro-blasting of coated cemented carbide inserts, on film's hardness and brittleness, cutting edge geometry as well as on tool life. To investigate the effect of the developed film compressive stresses at certain micro-blasting pressures and grain qualities on the film's brittleness, nano-impact tests were conducted. Moreover, roughness and cutting edge geometry measurements were carried out via co focal microscopy and EDX microanalyses after micro-blasting by Al_2O_3 or grains for detecting potential film thickness decrease and substrate revelation. The wear behavior of coated and variously micro-blasted tools was investigated in milling of hardened steel. The attained results provide insight concerning optimum selection of micro-blasting data in various grain cases, for improving the cutting performance of coated tools.

2.3 Graph Theory

Garg et al. (2006) developed a deterministic quantitative model based on graph theoretical approach. In this study a comparison is made between various technical and economical features of wind, hydro and thermal power plants and also used to evaluate and rank the power plants in ascending or descending order in accordance with the value of their suitability index. The

methodology present in this paper allows a decision maker to perform general analysis and other various focused analysis regarding his personal preferences.

Prabhakaran et al. (2006) used graph theory and matrix algebra to develop an integrated systems model for the structure of the composite product system in terms of its constituents and interactions between the constituents and the molding processes, curing kinetics etc. In this study a methodology is purposed for developing a composite product considering all attributes responsible for design, production, and process parameters. The composite product is first modeled with the help of graph theory, then by variable adjacency matrix and then by a multinomial known as permanent function. The permanent function has provided an opportunity to carry out structural analysis of the composite product in terms of strength, weakness, improvement, and optimization by correlating the properties of a composite with its structure.

Singh and Agrawal (2008) have presented a methodology for structural analysis of manufacturing system. In this study the identification of elements constituting a manufacturing system and the interactions between them is done and it has been represented by graph-based model. The matrix models and the variable permanent function models have been developed to carry out decomposition, characterization and the total analysis. In this work structural patterns and combination sets of subsystems interacting in various ways have been recognized as capabilities of manufacturing system. The permanent function of the manufacturing system matrix has been proposed as a systematic technique for structural analysis of manufacturing system.

Kiran et al. (2011) presented a methodology to develop a high quality product. This methodology combines all the design aspects of product together to generate a useful form of solution for the Mechatronic industry. This methodology considered all the x-abilities/design aspects along with interactions without missing any useful information. The methodology consists of graph theory, matrix algebra, and permanent multinomial. Eight x-abilities are indentified i.e. miniaturization, intelligence, integration, environment, quality, reliability, manufacturing, and assembly for concurrent design of a Mechatronic. For visual analysis a color graph is proposed.

2.4 Literature Summary

1. The effect of abrasive jet deburring processes on the surface finishing of jewellery models built by stereo lithography apparatus (SLA) was studied.
2. The abrasive machining characteristics of a glass-infiltrated alumina used for fabrication of all-ceramic dental crowns were investigated using a high-speed dental hand piece and diamond burs with different grit sizes.
3. Corrosion behavior of commercially pure titanium shot blasted with different materials and sizes of shot particles for dental implant applications was studied.
4. The response of material to particle impact during abrasive jet machining of alumina ceramics was studied.
5. The effect of shot blasting on plain fatigue and fretting fatigue behavior of Al–Mg–Si alloy AA6061 was analyzed.
6. The benefits to micro blasted tools, both coated and uncoated from shot blasting was studied and they resulted in greater productivity, lower cutting forces, improved surface finish of the work pieces and less machine downtime.
7. A method for removal of metal oxide layers formed on steel surfaces was developed as a dry decontamination technique for radioactively contaminated metal waste.
8. Effect of Grit-Blasting on the Surface Energy of Graphite/Epoxy Composites was investigated.
9. The erosion wear of the nozzle caused by abrasive particle impact was compared with dry sand blasting by determining the cumulative mass loss of the nozzles made from these materials.
10. The effect of grit blasting parameters on the surface roughness of Ti–6Al–4V alloy as the substrate for plasma-sprayed hydroxyapatite (HA) coatings was examined using the factorial and Taguchi designs of experiments.
11. Effects of grit blasting on surface properties of steel substrates were studied.
12. An approach was studied to create holes or grooves more efficiently via powder blasting process.
13. Influence of dry micro-blasting grain quality on wear behavior of TiAlN coated tools was examined.

14. Effect of slag ball blasting treatment on surface structure, roughness and wettability of 316LVM stainless steel was investigated.
15. A study was conducted to investigate how different parameters of the blast cleaning process affect properties and quality of brass parts surface.
16. A methodology is developed to combine all the design aspects of product together to generate a useful form of solution for the Mechatronic industry.
17. A methodology for structural analysis of manufacturing system is presented and the identification of elements constituting a manufacturing system and the interactions between them is done and it has been represented by graph-based model.
18. Graph theory and matrix algebra was used to develop an integrated systems model for the structure of the composite product system in terms of its constituents and interactions between the constituents and the molding processes, curing kinetics etc.
19. A deterministic quantitative model based on graph theoretical approach was developed and a comparison is made between various technical and economical features of wind, hydro and thermal power plants.

2.5 Gaps in Literature

There is lots of research done in the area of abrasive blasting. But still there are lot of areas still having scope of further research, which are written below.

1. The effect of different abrasives with different shape and size, on the surface roughness of different work materials.
2. The effect of different abrasive blasting processes like grit blasting, sand blasting, shot blasting, shot peening on the mechanical properties of different materials on which the research had not been done.
3. The effect of the processes like shot blasting for deburring, descaling on the materials like aluminium, aluminium alloys, soft steels and other materials having burrs and scale after conventional machining.
4. Extent to which a abrasive blasting process can be automated to make it fast and safe.
5. To find the different parameters and the limits of their variability which contributes to the effectiveness of abrasive blasting process.

6. Graph theory can be applied to carry out cause and effect analysis to find out the reasons of better performance of an abrasive blasting system.
7. The modeling, Characterization and integrative analysis of Abrasive blasting system can be done by applying graph theory.
8. Graph theory can be applied to compare different type of Abrasive blasting systems.

2.4 Work Objective

After finding the gaps in literature the objective of the work was to study the response of four different metals after blasting steel shots at the surface and the modeling of the abrasive blasting system by using Graph theory technique. The final objective was the modeling, analysis, evaluation and experimental investigation of abrasive blasting process.

CHAPTER-3

STRUCTURAL MODELLING AND INTEGRATIVE ANALYSIS OF ABS SYSTEM

3.1 Introduction to Graph Theoretic Approach

To fill the research gap and to show the importance of a structure based Abrasive blasting system design, a graph theory based Abrasive blasting system model is proposed. The model can include all the subsystems along with the interactions therein and thus becomes a tool for Abrasive blasting system analysis. A graph is required for visual analysis of an Abrasive blasting system, but quantification of these interactions is necessary for design and analysis. Matrix algebra is used for quantifying these interactions. A graph $G = (V, E)$ [1] consists of a set of objects $V = \{v_1, v_2, \dots\}$ called vertices or nodes, and another set $E = \{e_1, e_2, \dots\}$, of which the elements are called edges, such that each edge e_k is identified with a pair of vertices.

3.2 Assumptions for developing graph theoretic model

The proposed graph theoretic model for Abrasive blasting systems is based on some assumptions as listed below:-

- The structure of the system can be compared quantitatively with its performance.
- The interactions as well as the subsystems discussed are assumed for a general Abrasive blasting system.
- The subsystems must be identified separately for applying the model to any specific Abrasive blasting system.
- Variable permanent matrix is capable of storing complete information related to a real life situation of a typical Abrasive blasting system system as all its elements are variables and functions of characterizing attributes representing subsystem and interconnections. These attributes if identified comprehensively, the matrix represents the Abrasive blasting system completely.
- Permanent function of the variable permanent matrix characterizes uniquely the Abrasive blasting system from the point view of the structure.
- Performance of the Abrasive blasting system depends on individual performance of sub-systems and their components along with interactions between them.

- Modeling methodology is based on bottom-up approach. Permanent function values of sub-subsystems are used in permanent matrices of subsystems. Permanent function values of subsystems are used to calculate permanent functions of Abrasive blasting system.
- The experts may assign correct and representative score to the elements of the Abrasive blasting system at the lowest level in a particular dimension of performance.

3.3 Identification of Subsystems of the Abrasive blasting system and their Interactions

The Abrasive blasting system consists of large number of components i.e. RC circuits, blasting wheel, filter, storage tank, bucket elevators , controls, indicators, tools, servo controls etc. We can broadly divide ABS into 5 subsystems namely power supply unit, control panel, blasting unit, abrasive feed system and recycling unit. These sub systems further contains components in them as shown in following figure.

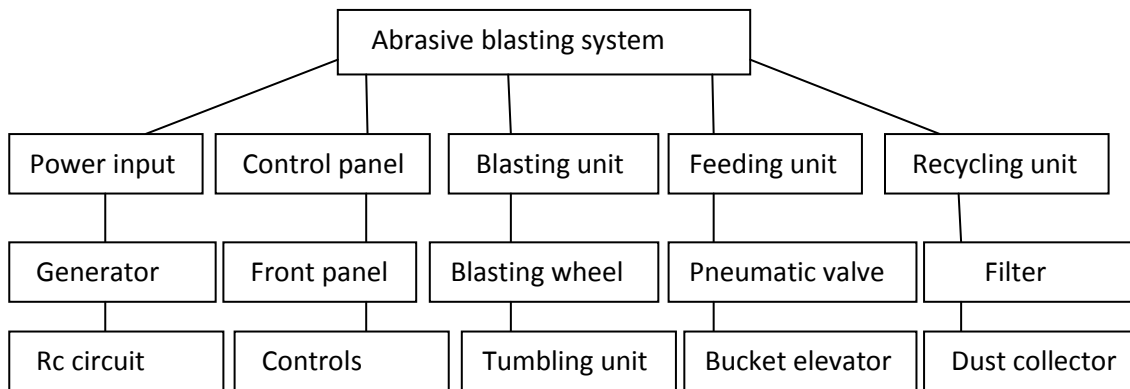


Figure 3.1 Abrasive blasting system and subsystems

Power supply unit Power supply unit mainly consists of generator and circuits. Several different electric circuits are available to provide the pulsating dc across the work tool gap. The suitability of circuit depends on the machining conditions and requirements. The commonly used principles for supplying the pulsating dc can be classified into three groups i.e. resistance capacitance

relaxation circuit with a constant dc source, Rotary impulse generator and controlled pulse circuit.

Control panel A control panel acts as a interface between machine and operator. It contains no. of controls each for performing different task. It consists of toggle switches, push buttons, indicator lamps , ammeter and alarms etc.

Blasting unit It consists of blasting wheel, work cabinet, tumbling unit etc. The work pieces should be placed in the work cabinet. The blasting wheel is mounted on the cabinet and tumbling unit performs the tumbling operations.

Feeding unit It consists of abrasive feeding unit having bucket elevator system and pneumatic valve. The valve performs the action of allowing the supply of abrasive from hopper unit the work pieces are placed in the cabinet.

Recycling unit This unit performs the cleaning and filtering of the used abrasives having FRL unit and dust collector for collection of filtered dust.

3.4 Graph Theoretic modeling of an Abrasive blasting system

The schematic diagram of Abrasive blasting system is a good representation of different identified components and their interactions which provides the good understanding of the structure of Abrasive blasting system, but it is not a mathematical entity. To overcome this problem, a graph theory based modeling of an Abrasive blasting system is proposed. A graph theory based mathematical model is derived for representing the physical structure of Abrasive blasting system along with interactions.

Five subsystems of Abrasive blasting system as shown in the Figure and interactions among them are represented using a digraph as shown in Figure. In general graph is represented mathematically by $G = \{V, E\}$; where V represents vertices of the graph and E represents the edges connecting between those vertices. In the Abrasive blasting system, let the vertices correspond to subsystems (V_i) and the edges (e_{ij}) correspond to interaction of its two sub systems. In Figure components of Abrasive blasting system are represented by the vertices of the graph and the interaction of the subsystems are represented by the edges of the graph. Undirected graph are used where directional property is not significant as shown in Figure. This means that the influence of i th vertex on j th vertex is equal to the influence of j th vertex on i th vertex. For directed graph i.e. digraph $e_{ij} \neq e_{ji}$.

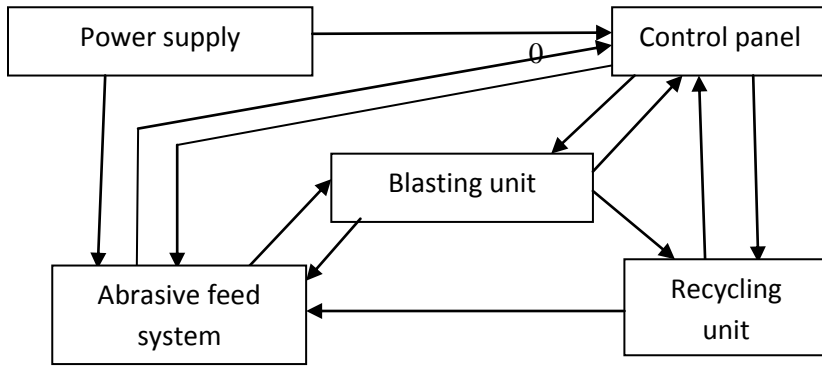


Fig. 3.2 Schematic representation of ABS

Let

S₁- Power Supply Unit

S₂- Control Panel

S₃- Blasting unit

S₄- Abrasive feed system

S₅- Recycling unit

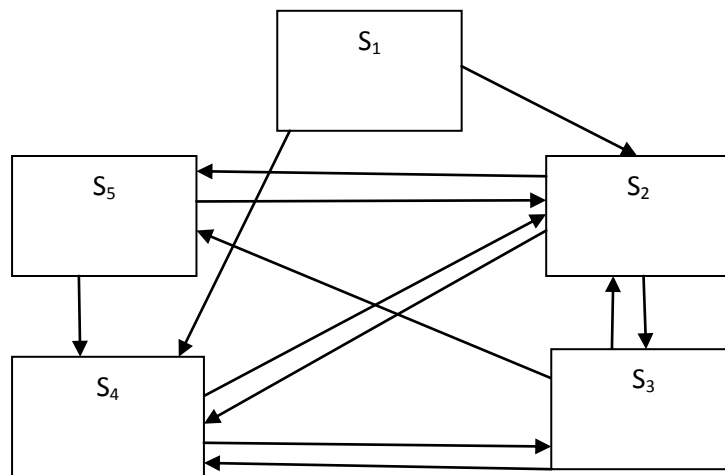


Fig. 3.3 Abrasive blasting system design

3.5 Matrix Representation for the Abrasive blasting system Graph

To quantify sub systems and interactions in Abrasive blasting system graph an equal mathematical representation known as Matrix is used. In general the graph is represented by a matrix called adjacency matrix. Since adjacency matrix represents the physical structure of an Abrasive blasting system, it is termed as Abrasive blasting system Structure Matrix.

3.5.1 Abrasive blasting system Matrix (ABSM)

Abrasive blasting system matrix is a square matrix, having rows and columns correspond to respective sub system. This matrix is a binary square matrix having (0, 1) as elements. Abrasive blasting system of N sub systems is represented by a structure matrix of size N x N. The system structure matrix of the AB system graph with four nodes will be a

Five order binary (0,1) square matrix, $\mathbf{A}=[e_{ij}]$ such that:

$$e_{ij} = \begin{cases} 1, & \text{if subsystem } i \text{ is connected to subsystem } j. \\ 0, & \text{otherwise} \end{cases}$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \end{bmatrix} \quad (1)$$

3.5.2 Abrasive blasting system Characteristic Matrix (ABSCM)

To characterize the Abrasive blasting system, a new matrix B is defined using the identity matrix \mathbf{I} , a variable λ which represents the Abrasive blasting system, and the adjacency matrix \mathbf{A} . Based

on the standard characteristic equation in mathematics, the ABS characteristic matrix **B** for the graph shown in Figure , may be expressed as $B = [\lambda I - A]$.

Where **I**= Identity Matrix

λ = variable representing Abrasive blasting system

$$\begin{matrix}
 & \lambda & -1 & 0 & -1 & 0 \\
 & -1 & \lambda & -1 & -1 & -1 \\
 \mathbf{B} = & 0 & 0 & \lambda & -1 & -1 \\
 & 0 & -1 & 0 & \lambda & 0 \\
 & 0 & -1 & 0 & -1 & \lambda
 \end{matrix} \tag{2}$$

$$\mathbf{Det}(\mathbf{B}) = \lambda^5 - 4\lambda^3 - 5\lambda^2 - 4\lambda$$

In Equation (2), the value of all diagonal elements is same (i.e., all Abrasive blasting system components are assumed to be identical which is not true in reality). In real situation different sub systems are having different physical structures and characteristics. Also interaction represented by a binary number 1 in matrix **B** does not provide information like type of interaction and degree of interaction. So, Equation (2) is not the complete representation of Abrasive blasting system structure. To overcome this problem, another matrix called the Abrasive blasting system variable characteristic matrix is proposed.

3.5.3 Abrasive blasting system Variable Characteristic Matrix (ABSVCM)

The Abrasive blasting system variable characteristic matrix takes into consideration, the effect of different ABS subsystem (i.e. components) and their varying degrees of interactions. The ABS structure graph in Figure is considered for defining this variable characteristic matrix **C** as below in Equation (3). For this purpose, a five order square matrix **E** with off-diagonal elements S_{ij} representing varying levels of interactions between the subsystems is defined. Another matrix **D**, a diagonal matrix with diagonal elements S_i $i=1,2,3,\dots,5$ representing five different subsystems

or components is defined. The matrix **C** can be developed from the matrices **E** and **D** as **C = [D – E]**

$$\mathbf{D} = \begin{matrix} & S_1 & 0 & 0 & 0 & 0 \\ & 0 & S_2 & 0 & 0 & 0 \\ & 0 & 0 & S_3 & 0 & 0 \\ & 0 & 0 & 0 & S_4 & 0 \\ & 0 & 0 & 0 & 0 & S_5 \end{matrix}$$

$$\mathbf{E} = \begin{matrix} & 0 & e_{12} & 0 & e_{14} & 0 \\ & 0 & 0 & e_{23} & e_{24} & e_{25} \\ & 0 & e_{32} & 0 & e_{34} & e_{35} \\ & 0 & e_{42} & e_{43} & 0 & 0 \\ & 0 & e_{52} & 0 & e_{54} & 0 \end{matrix}$$

$$\begin{aligned}
C = D - E = & \begin{matrix} S_1 & -e_{12} & 0 & -e_{14} & 0 \\ 0 & S_2 & -e_{23} & -e_{24} & -e_{25} \\ 0 & -e_{32} & S_3 & -e_{34} & -e_{35} \\ 0 & -e_{42} & -e_{43} & S_4 & 0 \\ 0 & -e_{52} & 0 & -e_{54} & S_5 \end{matrix} \quad (3)
\end{aligned}$$

$$\begin{aligned}
\text{Det (C)} = & [s_1 s_2 s_3 s_4 s_5] + [0] + [-s_1 s_2 s_5 e_{43} e_{34} - s_1 s_4 s_5 e_{32} e_{23} - s_1 s_3 s_5 e_{24} e_{42} - s_1 s_3 s_4 e_{25} e_{52}] + \\
& [-s_1 s_2 e_{43} e_{35} e_{54} - s_1 s_5 e_{23} e_{34} e_{42} - s_1 s_4 e_{23} e_{35} e_{52} - s_1 s_5 e_{32} e_{24} e_{43} - s_1 s_3 e_{25} e_{54} e_{42}] + [\\
& -s_1 e_{23} e_{35} e_{54} e_{42} - s_1 e_{24} e_{43} e_{35} e_{52} - s_1 e_{25} e_{54} e_{43} e_{32}] + [-s_1 e_{25} e_{52} e_{34} e_{43}] + [0] \quad (4)
\end{aligned}$$

The above matrix distinctly represents characteristic features of the subsystems and their interactions. Thus, the matrix **C** in Equation (3) is complete structural representation of the ABS system capturing all the data related to the system including the interactions. This information is useful for analysis, design, and development of new Abrasive blasting systems at conceptual stage or for optimization purposes. The matrix provides a powerful tool through its determinant, called the variable characteristic Abrasive blasting system multinomial. This is a characteristic of the system and represents the complete Abrasive blasting system, considering the effect of components and their interactions.

3.5.4 Abrasive blasting system Variable Permanent Matrix (ABSVPM)

The determinant of the matrix, **C** i.e., the variable characteristic Abrasive blasting system multinomial, includes both positive and negative signs. On substituting numerical values in place of diagonal and off-diagonal elements, some of the information is lost in the determinant. This

information loss is due to subtraction of some of the terms in the expression. To avoid information loss during mathematical process, another term Abrasive blasting system variable permanent matrix is introduced. Let the permanent matrix of five-subsystem be defined as

$$\begin{array}{cccccc}
 & S_1 & -e_{12} & 0 & -e_{14} & 0 \\
 & 0 & S_2 & -e_{23} & -e_{24} & -e_{25} \\
 Q = & 0 & -e_{32} & S_3 & -e_{34} & -e_{35} \\
 & 0 & -e_{42} & -e_{43} & S_4 & 0 \\
 & 0 & -e_{52} & 0 & -e_{54} & S_5
 \end{array}$$

3.6 Development of Permanent Function for Abrasive blasting system

To develop a unique and comprehensive model of Abrasive blasting system, another entity permanent matrix, frequently used in combinatorial mathematics is proposed. The permanent function is obtained from a similar manner as its determinant, but all negative terms obtained after expression for the calculation of the determinant of the matrix are replaced with positive equivalent terms. This computation results in a multinomial (Equation 5) whose every term has a physical significance related to the Abrasive blasting system. The multinomial representation includes all the information regarding various components as subsystems and interactions among them. The multinomial is derived based on Equation (4), and a numerical index is obtained. When the actual values of each term are substituted in the multinomial, the final values after the algebraic addition gives a numerical index, which can be considered as a score of total Abrasive blasting system in any performance dimension depending upon the one selected for giving values to the individual structural constituents. This score can prove a powerful tool for comparison, ranking of different Abrasive blasting systems and optimum selection of Abrasive blasting system. Thus permanent function is proposed s a complete tool for the total structural analysis of the Abrasive blasting system. The variable permanent function for an Abrasive blasting unit derived from Equation (4) is as follows:

$$\begin{aligned} \text{Per (Q)} = & S_1S_2S_3S_4S_5 + S_1S_2S_5e_{43}e_{34} + S_1S_4S_5e_{32}e_{23} + S_1S_3S_5e_{24}e_{42} + S_1S_3S_4e_{25}e_{52} + S_1S_2 e_{43} \\ & e_{35} e_{54} + S_1S_5 e_{23} e_{34} e_{42} + S_1S_4 e_{23} e_{35} e_{52} + S_1S_5 e_{32} e_{24} e_{43} + S_1S_3 e_{25} e_{54} e_{42} + S_1 e_{23} e_{35} \\ & e_{54} e_{42} + S_1 e_{24} e_{43} e_{35} e_{52} + S_1 e_{25} e_{54} e_{43} e_{32} + S_1 e_{25} e_{52} e_{34} e_{43} \end{aligned} \quad (5)$$

Every term of these equations represents a subset of the Abrasive blasting system. To achieve this objective and for the unique representation and interpretation, the permanent function is written in a standard form as $(N + 1)$ groups, where N is the number of subsystems. The permanent function when written in $(N + 1)$ groups present an exhaustive way of analysis of an Abrasive blasting system at different levels. The multinomial consists of different combinations of Abrasive blasting system interaction components for example, structural constituents such as subsystem characteristics (S_i 's) and structural interactions (S_{ij} 's). The existence of elements such as S_{2ij} or $S_{ij} S_{ji}$, S_{ij} , $S_{jk}.S_{ki}$, $S_{ij}.S_{jk}.S_{kl},S_{li}$, etc. correspond to the subsystems interacting in the form of a dyad, two subsystem loop, four subsystem loop, etc. respectively. The terms in each group of the multinomial form a separate group, which may be used for characterizing the Abrasive blasting system uniquely. The permanent function has terms in different groups as follows:

- The first group contains only isolated five components are to be considered together as independent entities.
- The second group is absent, because the system has no term with four subsystems.
- The third group has one terms, it is a combination of three dyad $S_1S_2S_5$ and one loop L_{34} .
- The fourth group has two terms, first term is a combination of two dyad S_1S_2 and one loop L_{354} and second term is a combination of two dyad S_1S_5 and one loop L_{234} .
- The fifth group has only two terms in which first contains a dyad S_1 and loop L_{2435} and other term contains one dyad and two loops L_{25}, L_{34} .
- The sixth group is absent because the the system has no term with only single loop.

So equation 5 can be written in terms of loops as follows:

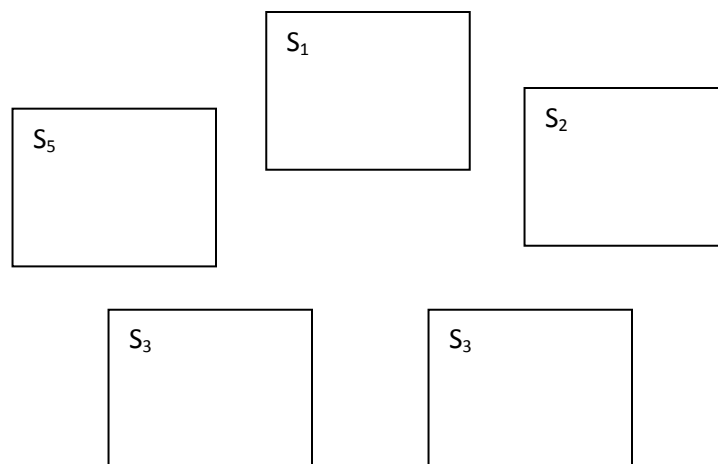
$$\begin{aligned} \text{Per (Q)} = & S_1S_2S_3S_4 S_5 + S_1S_2 S_5L_{34} + S_1 S_4S_5L_{23} + S_1 S_3 S_5L_{24} + S_1 S_3S_4L_{25}+ S_1 S_2L_{354} + S_1 S_5 \\ & L_{234} + S_1 S_4 L_{235} + S_1 S_5 L_{243} + S_1 S_3L_{254} + S_1 L_{2354} + S_1 L_{2435}+ S_1L_{2543} + S_1 L_{25}L_{34} \end{aligned} \quad (6)$$

The multinomial defined in Equation (5), gives a unique numerical index which is defined as:

$$\text{Abrasive blasting system numerical index} = \text{Per}(\mathbf{Q}) \text{ (after substituting numerical values in the matrix } \mathbf{Q}) \quad (7)$$

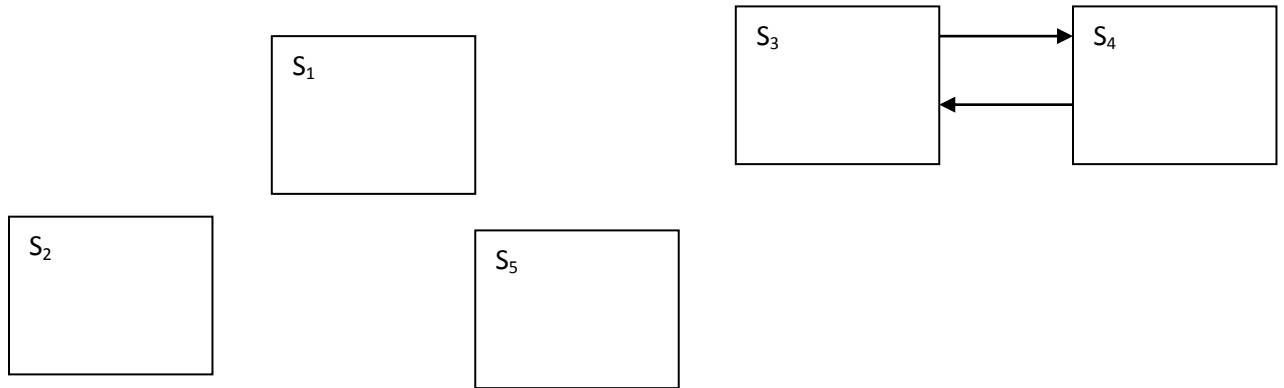
Researchers can assign the numerical values to various subsystems as well as the interactions, depending on the type of Abrasive blasting system and according to parameters of ABS machine i.e. current, tool material and work piece material etc. For complex subsystems, the numerical values may be assigned by splitting the subsystem into further lower subsystems and their permanent function may be used as the numerical score for the subsystem i.e. separate graph, matrix, or index can be derived for each subsystem using the same procedure. To calculate correct degree of interactions between the subsystems, we may have to consider the views of technical team experts. This numerical index is considered as a composite score of total Abrasive blasting system depending upon the type of system and interactions between its subsystems. This score can prove a powerful tool for comparison, ranking of different Abrasive blasting systems and optimum selection of Abrasive blasting system.

Group1



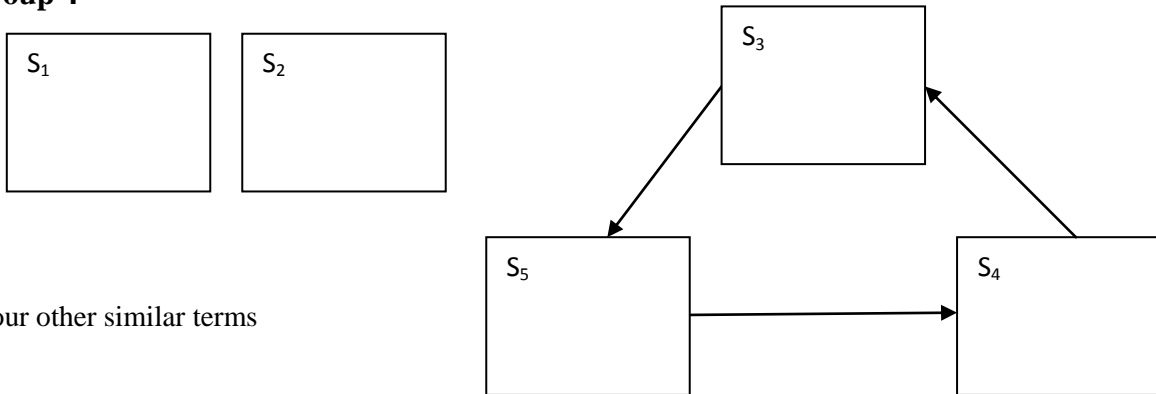
Group 2 This group is absent.

Group 3



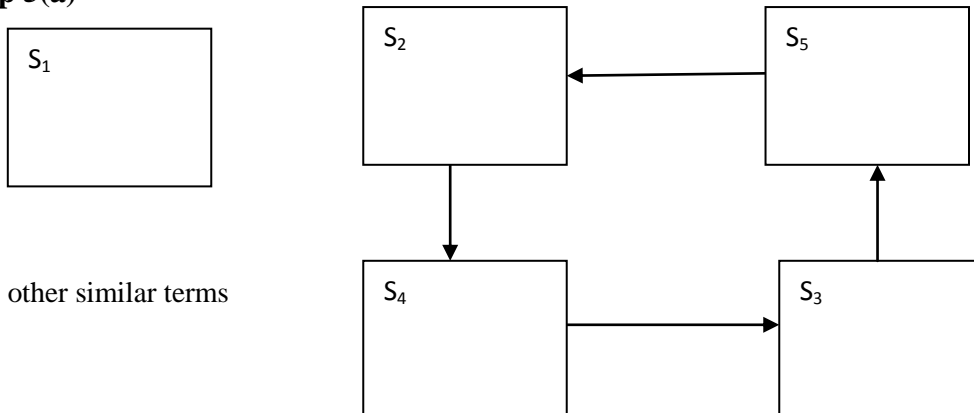
+ three other similar terms.

Group 4



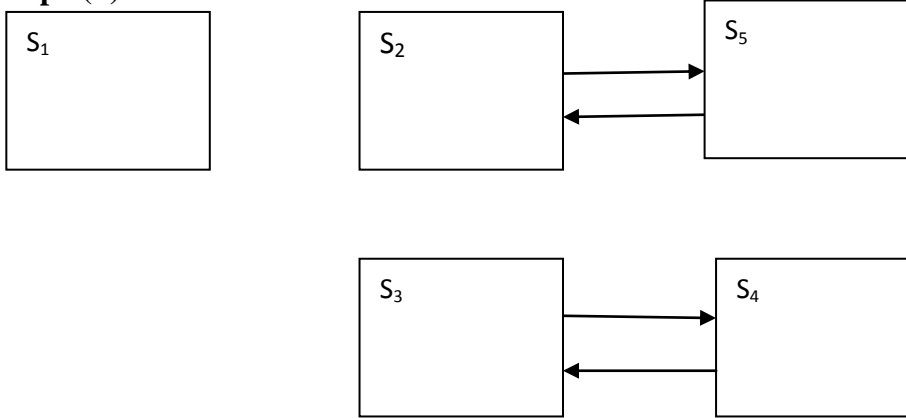
+ four other similar terms

Group 5(a)



+ two other similar terms

Group 5(b)



Group 6 This group is absent.

Figure 3.4 Physical representation of permanent function for Abrasive blasting system

3.7 Identification and Comparison of Abrasive blasting system

The Abrasive blasting system permanent function is useful for identification and comparison of Abrasive blasting system structures. The number of terms in each grouping of the Abrasive blasting system permanent function for all kind of Abrasive blasting systems for a given set of components will be same. However, their values will be different. Two Abrasive blasting systems may be similar from the qualitative aspects, if their system structure graphs are isomorphic. Two such graphs are isomorphic, if they have identical permanent function matrix set representation. This means not only the number of terms in the groupings as well as sub-grouping as same but also their values are also same. Based on this, system structure identification set of Abrasive blasting units is represented as

$$[(M_{1T}/M_{2T}/M_{3T}/M_{4T}/M_{51T}/M_{52T}/M_{61T}/M_{62T}/\dots)(N_{1T}/N_{2T}/N_{3T}/N_{4T}/N_{51T}/N_{52T}/N_{61T}+N_{62T}/\dots) \quad (8)$$

Where $M_{i T}$ represents the total number of terms in the i th grouping, M_{ijT} represents the total number of terms of the M th sub grouping in the i th grouping. Similarly, $N_{i T}$ represents the numerical value of the i th grouping and N_{ijT} represents the numerical value of the M th sub

grouping in the i th grouping. Numerical values of the S_i 's and S_{ij} 's are substituted in the sub grouping or the grouping to obtain the permanent system numerical index.

3.8 Generalization of the permanent function

For general Abrasive blasting system with N subsystems, the Abrasive blasting system characteristic and interdependence matrix, Q may be written as in Equation (9) below:

$$Q = \begin{matrix} & S_1 & S_{12} & \dots & S_{1N} \\ S_{21} & S_2 & \dots & S_{2N} \\ \dots & \dots & \dots & \dots \\ S_{N1} & S_{N2} & \dots & S_N \end{matrix} \quad (9)$$

For general N subsystem Abrasive blasting system with all the subsystems linked together, the total number of terms of the permanent function shall be equal to $N!$ The permanent for the above matrix, i.e., per (Q) is called variable permanent function. The variable permanent function for the above matrix is written in sigma (Σ) form as

$$\begin{aligned} \text{Per } (Q) = & \Pi^N S_i + \Sigma_i \Sigma_j \Sigma_k \dots \Sigma_N (S_{ij} S_{ji}) S_k S_l \dots S_N \\ & + \Sigma_i \Sigma_j \Sigma_k \dots \Sigma_N (S_{ij} S_{ik} S_{ki} + S_{ik} S_{kj} S_{ji}) S_l S_m \dots S_N + \\ & \{ \Sigma_i \Sigma_j \Sigma_k \dots \Sigma_N (S_{ij} S_{ji}) (S_{kl} S_{lk}) S_m S_n \dots S_N + \\ & \Sigma_i \Sigma_j \Sigma_k \dots \Sigma_N (S_{ij} S_{ik} S_{kl} S_{li} + S_{il} S_{lk} S_{kj} S_{ji}) S_m S_n \dots S_N \\ & + \dots \dots \dots \end{aligned} \quad (10)$$

3.9 Abrasive blasting system Analysis

The methodology described in this chapter for complete analysis of Abrasive blasting system is summarized in step-by-step manner as below:

1. Select the desired Abrasive blasting system. Study the system and its subsystems and also their interactions.

2. Develop a system graph of the Abrasive blasting system with subsystems as vertices and edges for interaction between the vertices.
3. Using the graph in step 2, develop matrix similar to Abrasive blasting system variable permanent matrix given in Equation (5).
4. Calculate system permanent function.
5. The numerical index of an Abrasive blasting system would be obtained by substituting the numerical values of subsystems and their interactions.

3.10 Usefulness of the Methodology

The proposed approach is useful for product design engineer, researcher, and industries at conceptual stage. This methodology is useful while

1. Taking decision for purchasing ABS machine from different types available for given application.
2. Carrying out cause and effect analysis to find out the reasons of difference in performance of any Abrasive blasting system.
3. Carrying out SWOT (Strength-Weakness-Opportunity-Threats) analysis on Abrasive blasting system.
4. Carrying out re-engineering of the product, process etc. for break through improvement.
5. Increasing the product life cycle of the ABS machine.
6. Developing maintenance strategies.
7. The methodology is dynamic in nature as sub-systems/components and interactions, which appear as variables in different models may be changed without any difficulty.

CHAPTER 4

Experimental set-up and Equipments used

4.1 Experimental set-up To study the effect of abrasive blasting on the surface of different materials the parameters like surface roughness, hardness, percentage mass loss and surface composition were required to be studied. The experimental set up is explained below.

4.1.1 Materials used as work pieces

- Mild steel (99% Fe, 0.101% C, 0.173% Si, 0.532% Mn)
- Die steel (H11) (90.5% Fe, 0.397% C, 0.865% Si, 5.24% Cr, 1.10% Mo)
- Cast iron (91.5% Fe, 2.16% C, 1.16% Si, 0.606 Mn)
- Aluminium (92.6% Al, 1.2 % Mn, 6.44% Ni, 0.164% Cr)

4.1.2 Blasting material

Round steel shots, Size = 0.425mm size, Grade = S170

Chemical composition = carbon 0.6 to 1.25%, silicon 0.2 to 1.1%, manganese 1.25% max., sulphur 0.08% max., phosphorous 0.08% max.

4.1.3 Levels of Blasting time taken

5min, 10min, 15min, 20min, 25min, 30min

4.1.4 Output tests

Micro hardness test, Surface roughness test, Percentage weight loss test and Chemical composition test

Experimental setup table 4.1

Work piece material	Abrasive blasting Time (minutes)					
	Cast iron	5	10	15	20	25
Mild steel	5	10	15	20	25	30
Die steel (h11)	5	10	15	20	25	30
Aluminium	5	10	15	20	25	30

4.2 Equipments and machines used.

4.2.1 Abrasive blasting machine A tumbling-blast machine model ATB (Automatic Tumble Blast) by Mec Shot Blasting equipments, INDIA is used for blasting operation. It consists of an enclosed, endless conveyor belt, a centrifugal blast wheel and an abrasive recycling system. These machines simultaneously tumble and blast the work pieces. As the conveyor moves, it gently tumbles the work and exposes all work piece surfaces to the abrasive system.

Specifications of Abrasive blasting machine.

1. Working chamber

Length×width×height : 1360×1500×1600mm

2. Sliding door

Width×height : 750×700mm

Liners : 6mm thick manganese Liners



Fig. 4.1 (ATB) Automatic tumble blasting machine

(Courtesy; NON Traditional machining Lab, Thapar University, Patiala)

3. Belt tumbler

Belt size : 1320×4925×17mm

Belt drive motor : 1HP

4. Bucket elevator

Motor : 1HP

Elevator bucket : 10×100×7688mm

No. of buckets : 32

5. Dust collector

Blower capacity : 1200CFM

Motor : 3HP

Filter bags : 24 Nos.

6. Blast wheel unit

Size of blast wheel : 12.5" × 2.5"

Motor for blast wheel : 7.5HP

4.2.2 Surface Roughness Tester

Surface roughness was measured using the Mitutoyo model SJ-400, Germany. The equipment uses the stylus method of measurement, has profile resolution of 12 nm and measures roughness up to 100 µm. A tracing length of 4.8 mm was used for analysis. Surface Roughness values were taken two times for each trial and average was used for analysis.



Fig. 4.2 Surface roughness tester Mitutoyo model SJ-400.

(Courtesy ; Metrology Lab, Thapar University, Patiala)

4.2.3 Optical Emission Spectrometer

Chemical composition of the workpiece base materials and the composition of machined surfaces is measured using Optical Emission Spectrometer (Model: DV-6), Baird, USA. An accuracy of 0.0001 % is achieved in the measurement. Argon gas is used for composition measurement process.



Fig. 4.3 Optical Emission Spectrometer (Model: DV-6), Baird, USA.

(Courtesy ; Metallurgy Lab, Thapar University, Patiala)

4.2.4 Micro Hardness Tester

Micro hardness was measured on a computer interfaced Micro Hardness Tester (Model: MVH-2), Meta tech industries, Pune, India available at Thapar University, Patiala. The micro hardness measurement is dependent on the diameter of indentation produced on the samples. The indents formed by the pyramid shaped indenter using a load of 1 Kg for 20 s and were measured with Quantimet software. 40 MP camera was used for observing / focusing images.



Fig. 4.4 Micro Hardness Tester (Model: MVH-2), Meta tech industries, Pune

(Courtesy; Metallurgy Lab, Thapar University, Patiala)

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Surface Hardness Test

Micro hardness was measured on a computer interfaced Micro Hardness Tester (Model: MVH-2), Metatech industries, Pune, India available at Thapar University, Patiala. The micro hardness measurement is dependent on the diameter of indentation produced on the samples. The indents formed by the pyramid shaped indenter using a load of 1 Kg for 20 s and were measured with Quantimet software. 40 MP camera was used for observing / focusing images. The values of microhardness (VHN) of different samples of different blasting times was given below in surface hardness values table.

Table 5.1 Surface Hardness values

Blasting Time (minutes)	Before blasting			5min			10min		
Surface Hardness value (VHN)									
Work piece material	1	2	Avg.	1	2	Avg.	1	2	Avg.
Cast iron	76.60	72.20	74.4	84.40	85.12	84.71	92.62	88.18	90.40
Mild steel	62.48	60.22	61.75	79.26	77.12	77.18	86.13	86.71	86.42
Die steel (H11)	80.35	78.25	79.30	84.28	92.10	88.19	113.20	119.62	116.42
Aluminium	31.10	33.48	32.29	48.30	50.64	49.47	52.32	56.04	53.18

15min			20min			25min			30min		
1	2	Avg.	1	2	Avg.	1	2	Avg.	1	2	Avg.
103.8	99.08	101.4	108.37	106.2	107.31	108.12	106.72	107.42	108.16	110.72	109.41
96.06	96.16	94.16	101.18	97.06	99.12	101.08	103.24	102.16	106.38	100.42	103.40
126.1	128.10	127.1	131.56	135.6	133.31	136.34	138.62	137.48	136.94	139.06	137.50
56.24	56.60	56.42	62.19	58.01	60.10	62.42	58.38	60.80	61.10	64.42	62.36

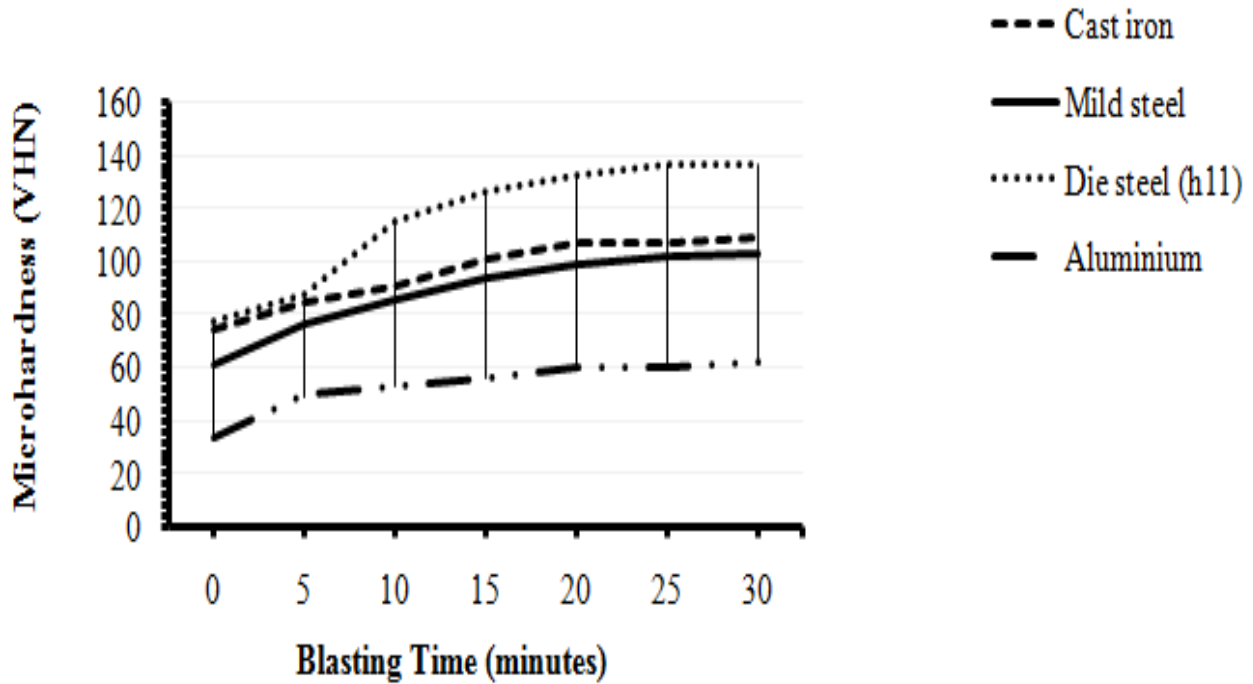


Fig 5.1 Graph Micro Hardness versus Blasting Time

The graph of micro hardness of the samples was given above. It shows that the micro hardness of all the materials increased with increase in blasting time. This indicates that the physical properties, particularly the hardness and density, of these particles are sufficient to induce plastic deformation and micro structural evolution at the surface. It has been reported that the particle impacts during the shot blasting treatment cause the formation of fine grains, residual stress and martensites which subsequently enhance the subsurface micro hardness [Arifvianto et al.]. The duration of shot blasting influences the magnitude of the resulting surface micro hardness. As shown in table the VHN (Vickers Hardness Number) of aluminium was 32.29 before blasting and after 15 minutes it increases to 56.42 and further increases to 62.36 after 30 minutes of blasting. Similarly for mild steel ,die steel and cast iron micro hardness at the was increased with blasting time up to certain period of blasting time then after 20 minutes of blasting there is very less change in the surface micro hardness value. The VHN of cast iron after 20min blasting was 107.31, after 25 min of blasting it increased marginally to become 108.16. Again after 30min blasting of cast iron it again only increased up to 109.41 Similarly, for die steel(H11) there was a sharp increase in hardness at surface initially but after 20 min of blasting the change is very less than it shows for all the four work piece materials the change in surface harness was very

significant and after further increase in blasting time does not make any major change in micro hardness.

5.2 Surface Roughness test

Surface roughness was measured using the Mitutoyo model SJ-400, Germany. The equipment uses the stylus method of measurement, has profile resolution of 12 nm and measures roughness up to 100 μm . A tracing length of 4.8 mm was used for analysis. Surface Roughness values were taken two times for each trial and average was used for analysis.

Table 5.2 Surface Roughness values

Blasting Time (minutes)	Before blasting			5min			10min		
Surface Roughness Value (R_a)									
Work piece material	1	2	Avg.	1	2	Avg.	1	2	Avg.
Cast iron	0.40	0.46	0.43	6.89	6.93	6.91	5.92	5.98	5.95
Mild steel	0.66	0.62	0.64	4.40	4.22	4.31	4.15	4.49	4.32
Die steel (H11)	0.72	0.82	0.77	3.43	3.87	3.65	4.04	4.56	4.30
Aluminium	1.07	1.023	1.15	8.53	8.27	8.35	6.92	7.04	6.96

15min			20min			25min			30min		
1	2	Avg.	1	2	Avg.	1	2	Avg.	1	2	Avg.
5.93	5.97	5.95	5.52	5.62	5.57	5.46	5.68	5.57	5.36	5.12	5.24
4.36	4.18	4.27	4.02	4.12	4.07	3.82	3.98	3.90	5.12	3.94	3.92
4.33	4.11	4.22	4.18	4.24	4.21	4.02	4.18	4.10	3.68	3.72	3.70
6.13	6.03	6.08	6.05	5.93	5.97	5.99	5.71	5.85	5.63	5.27	5.45

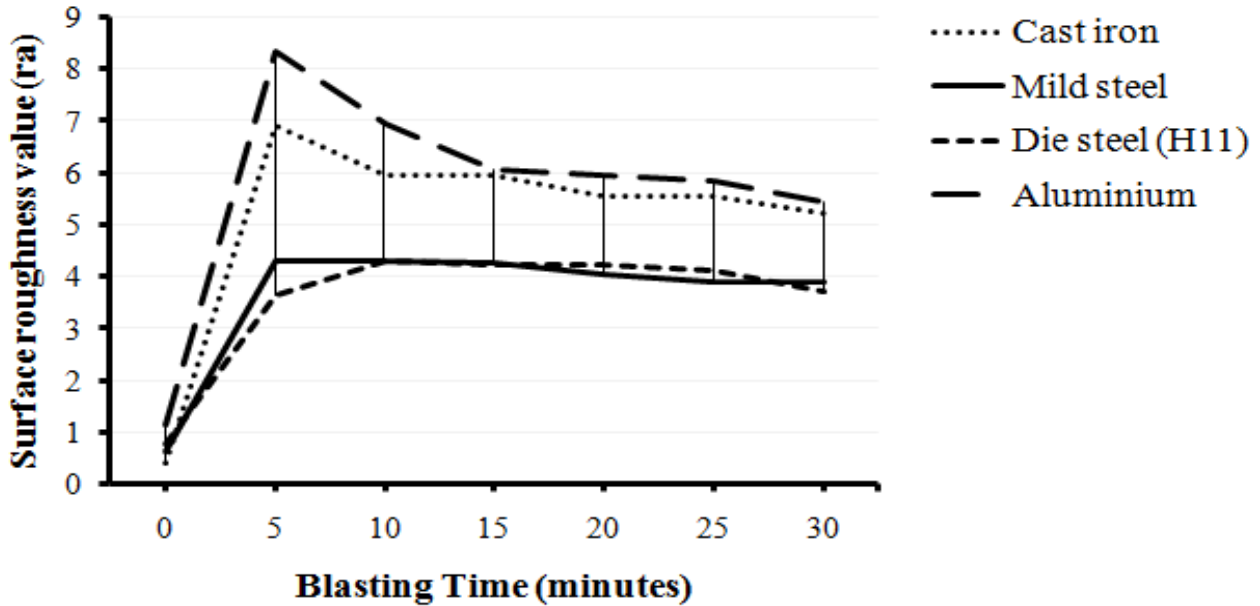


Fig. 5.2 Graph surface Roughness versus Blasting Time

The graph given above shows that the surface roughness evolution during the shot blasting with steel shots balls. The surface roughness of all the different samples increases rapidly during the first 5 min of the treatment. As for cast iron from $R_a=0.43R_a$ to $6.61 R_a$. A low rate of roughness reduction occurs after the maximum roughness value is achieved. As for aluminium after achieving the $8.31 R_a$ value of surface roughness for first 5 minutes it decreased to 6.96 then after 30 min blasting it further decreased to 5.45 . The shot blasting for duration longer than 20 min even does not yield a significant roughness reduction and seems to generate roughness saturation after 20 min of blasting for all samples. It also showed that the initial evolution of surface roughness after 5 min of shot blasting is more in softer material aluminium that was $83.1R_a$ than the harder material Die steel (H11) which was 3.87 . The surface roughness evolution during the shot blasting treatment as well as the other surface mechanical treatment seems also being influenced by the change in subsurface micro hardness by this treatment. Since the hardness determines material deformation and removal a less hard surface as in the beginning of the shot blasting treatment is more susceptible to severe deformation. The formation of new craters and pile-up therefore occurs easily. The increasing subsurface micro hardness during the shot blasting treatment increases the resistance of the surface against impact-induced deformation. Stages I (5) min and II (15 min) of the roughness evolution still result to a less hard surface than that produced in stage III. In stage I, the craters and pile-up are easily and quickly produced by

the impact of steel slag balls; yielding a sharp increase of surface roughness. A reduction of surface roughness in stage II indicates that the surface hardness of the specimen still allows the steel slag balls to deform this layer. However, the harder surface layer in stage II than that in stage I decreases the rate of roughness modification. The longer blasting duration increases the subsurface micro hardness and is consequently able to resist further surface deformation. A roughness saturation or stage III is therefore observed after (20) min of the treatment [Arifvianto et al.].

5.3 Percentage Mass loss

The mass loss that occurs on the specimen due to the shot blasting treatment was indicated by the percentage of mass reduction of the specimen after the treatment (M) and expressed mathematically in this equation. $M = \left(1 - \frac{m_{treat}}{m_{int}}\right) \times 100\%$

For this case, m_0 and m_t are the mass of the samples before and after the treatment, respectively. The samples were weighed before and after the treatment to obtain m_{int} and m_{treat} respectively.

Table 5.3 Percentage Mass loss values

Basting Time (minutes)	05min	10min	15min	20min	25min	30min
Work piece material	Percentage Mass loss after blasting					
Cast iron	0.148	0.270	0.421	0.638	0.819	0.995
Mild steel	0.142	0.173	0.275	0.387	0.398	0.479
Die steel (H11)	0.057	0.086	0.115	0.138	0.144	0.152
Aluminium	0.722	0.990	1.120	1.274	1.393	1.455

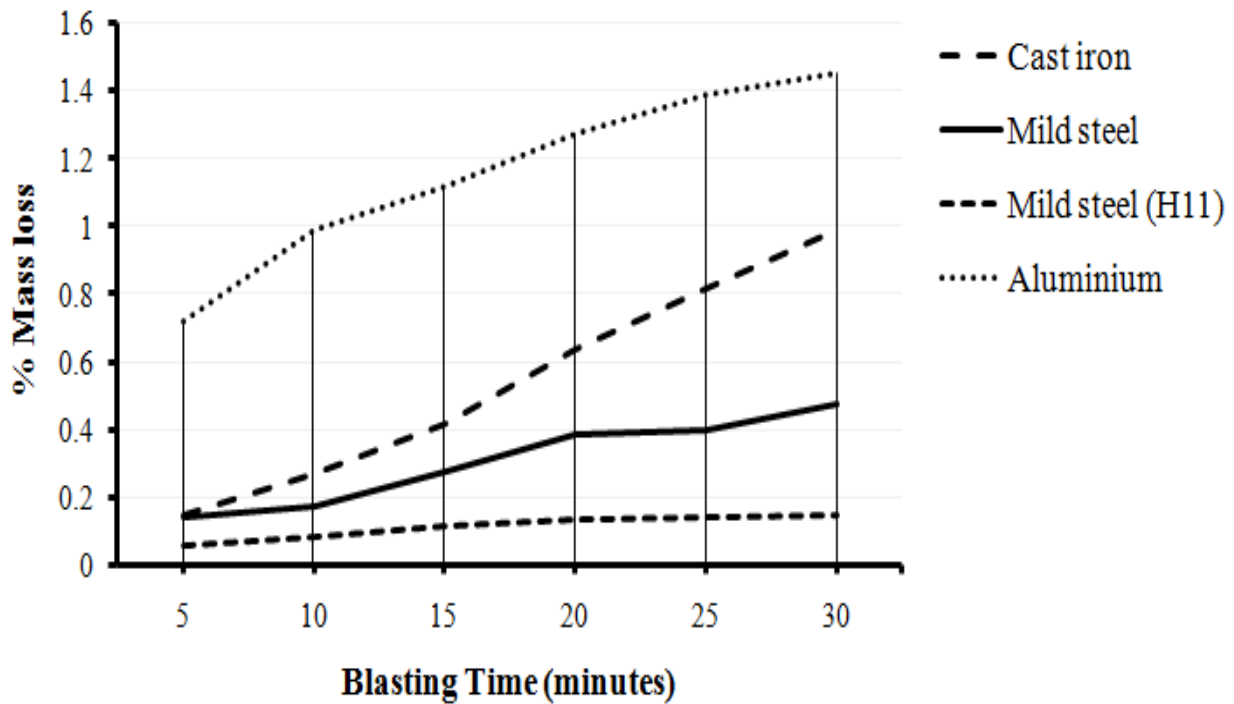


Fig. 5.3 Graph of Percentage Mass Loss versus Blasting Time

The graph above shows the percentage of mass loss during the shot blasting treatment using the steel shots. The blasting treatment using steel shots for 5–30 min reduces the mass of the samples. The treatment for 5 min is only able to yield a mass loss of 0.057Percentage for the die steel which was very low, but for the softer material aluminium it was 0.722Percentage. After 30 mins of blasting the Percentage weight loss for aluminium was 1.455 and for die steel it was only 0.152. The mass loss measured during the shot blasting treatment indicates material removal of the specimen surface due to the impact with the steel shot balls. In principle, the mass loss corresponds to the cutting action by the steel slag balls during the shot blasting treatment. The mass loss in the current study increases by the duration of shot blasting treatment but occurs with a lower rate after 20 min of processing. This finding is also influenced by the enhanced subsurface micro hardness by the duration of the shot blasting. It is well understood that the rate of surface material removal during the impacts with blasting particles decreases by the increasing surface hardness [Reidl et al. 2012]. The high rate of mass reduction during the first 20 min of shot blasting treatment is due to the relatively low subsurface hardness of the specimen. The shot

blasting for 20 min yields a harder surface and subsurface layer than those processed with a shorter time. Therefore, a greater resistance against surface material removal is seen for 20 min of shot blasting [Arifvianto et al. 2012].

5.4 Spectroscopy test

Chemical composition of the work piece base materials and the composition of machined surfaces is measured using Optical Emission Spectrometer (Model: DV-6), Baird, USA. An accuracy of 0.0001 Percentage is achieved in the measurement. Argon gas is used for composition measurement process.

Table 5.4 Chemical Composition of Cast Iron

Blasting time	0	5	10	15	20	25	30
Element	Percentage composition						
Fe	91.5	94.1	94.9	95.2	94.9	96.0	96.8
C	2.16	2.66	2.99	2.56	2.71	2.18	2.85
Si	1.76	1.68	1.65	1.63	1.75	1.09	1.12
Mn	0.606	0.486	0.4880	0.452	0.471	0.4781	0.443
P	0.168	0.147	0.184	0.145	0.188	0.157	0.203
Cr	0.0649	0.0614	0.0645	0.0633	0.699	0.0774	0.722

Table 5.5 Chemical Composition of Mild steel

Blasting time	0	5	10	15	20	25	30
Element	Percentage composition						
Fe	99.0	98.8	99.0	99.0	98.9	98.6	98.5
C	0.101	0.158	0.156	0.160	0.105	0.192	0.190
Si	0.173	0.227	0.202	0.191	0.203	0.192	0.332
Mn	0.532	0.570	0.553	0.542	0.564	0.566	0.584
P	0.0124	0.0169	0.0268	0.0296	0.0229	0.0200	0.203
Cr	0.0649	0.0614	0.0645	0.0633	0.699	0.0774	0.0722

Table 5.6 Chemical Composition of Die Steel (H11)

Blasting time	0	5	10	15	20	25	30
Element	Percentage composition						
Fe	90.5	90.5	90.8	90.2	90.8	90.0	90.6
C	0.397	0.389	0.418	0.432	0.448	0.391	0.430
Si	0.865	0.841	1.01	1.63	0.825	0.966	0.956
Mn	0.420	0.443	0.429	0.452	0.417	0.530	0.407
Cr	5.24	5.17	4.90	5.12	5.40	5.41	5.21
Mo	1.10	1.06	1.05	1.03	1.12	1.02	1.07

The surface chemical composition of the specimen is altered after the shot blasting treatment. The result of spectroscopy reveals some identical elements at the specimen surface with those at the steel slag ball, such as C, P, S, Ca, Si, Mg and Al together with Fe, Ni and Cr those are also present in the original samples. As the percentage of carbon composition in mild steel and die steel increased marginally that was contributed towards increase in hardness. There was little increase in phosphorous in cast iron which in small amounts, aided strength and corrosion resistance. Phosphorus additions are known to increase the tendency to cracking during welding. Small increase in chromium leads to increase resistance to oxidation. The above spectroscopy test of samples shows that there was very small change in composition of materials at the surface with change in blasting time. After 20mins of blasting there is hardly any change in the chemical composition of treated samples.

CHAPTER 6

Conclusion and Further scope of work

6.1 Conclusion

The graph theory applied to Abrasive blasting system provides general equation also the permanent function. The numerical index of an Abrasive blasting system would be obtained by substituting the numerical values of subsystems and their interactions which is very useful in carrying out cause and effect analysis, carrying out SWOT (Strength-Weakness-Opportunity-Threats) analysis on Abrasive blasting system, carrying out re-engineering of the product, process etc. for break through improvement, Increasing the product life cycle of the ABS machine, developing maintenance strategies.

The effect of shot blasting treatment using steel shot balls on the surface characteristics of four different metals was studied in this work. The impacts of steel shot balls are able to enhance the surface micro hardness, surface irregularity and roughness of the stainless steel. The duration of shot blasting influences the magnitude of the resulting surface micro hardness. It was found that the VHN (Vickers Hardness Number) of aluminium was 32.29 before blasting and after 15 minutes it increases to 56.42 and further increases to 62.36 after 30 minutes of blasting. Similarly for mild steel, die steel and cast iron micro hardness at the was increased with blasting time up to certain period of blasting time then after 20 minutes of blasting there was very less change in the surface micro hardness value. The VHN of cast iron after 20min blasting was 107.31, after 25 min of blasting it increased marginally to become 108.16. Again after 30min blasting of cast iron it again only increased up to 109.41 Similarly, for die steel (H11) there was a sharp increase in hardness at surface initially but after 20 min of blasting the change was very less than it shows for all the four work piece materials the change in surface harness was very significant and after further increase in blasting time does not make any major change in micro hardness.

Surface roughness was desirable in some situations like, before coating. The surface roughness of all the different samples increases rapidly during the first 5 min of the treatment. As for cast iron from $R_a=0.43R_a$ to $6.61 R_a$. A low rate of roughness reduction occurs after the maximum roughness value is achieved. As for aluminium after achieving the $8.31 R_a$ value of surface roughness for first 5 minutes it decreased to 6.96 then after 30 min blasting it further decreased to 5.45. The shot blasting for duration longer than 20 min even does not yield a significant

roughness reduction and seems to generate roughness saturation after 20 min of blasting for all samples. It also showed that the initial evolution of surface roughness after 5 min of shot blasting was more in softer material aluminium that was 83.1R_a than the harder material Die steel (H11) which was 3.87. The surface roughness evolution during the shot blasting treatment as well as the other surface mechanical treatment seems also being influenced by the change in subsurface micro hardness by this treatment. Since the hardness determines material deformation and removal a less hard surface as in the beginning of the shot blasting treatment was more susceptible to severe deformation. The formation of new craters and pile-up therefore occurs easily. The increasing subsurface micro hardness during the shot blasting treatment increases the resistance of the surface against impact-induced deformation. Stages I (5) min and II (15 min) of the roughness evolution still result to a less hard surface than that produced in stage III. In stage I, the craters and pile-up are easily and quickly produced by the impact of steel slag balls; yielding a sharp increase of surface roughness. A reduction of surface roughness in stage II indicates that the surface hardness of the specimen still allows the steel slag balls to deform this layer. However, the harder surface layer in stage II than that in stage I decreases the rate of roughness modification. The longer blasting duration increases the subsurface micro hardness and was consequently able to resist further surface deformation. A roughness saturation or stage III was therefore observed after (20) min of the treatment.

The surface chemical analysis reveals the presence of several contaminants such as C, S, P, Si and Mg on the specimen surface after being blasted with the steel slag balls. These particles contribute towards improving the surface properties of metals. In addition, material removal occurs during the blasting treatment with these particles.

The mass loss during steel shot blasting was very low and not very significant for hard metal. mass loss during the shot blasting treatment using the steel shots. The blasting treatment using steel shots for 5–30 min reduces the mass of the samples. The treatment for 5 min was only able to yield a mass loss of 0.057Percentage for the die steel which was very low, but for the softer material aluminium it was 0.722 Percentage. After 30 minutes of blasting the Percentage weight loss for aluminium was 1.455 and for die steel it was only 0.152. The mass loss measured during the shot blasting treatment indicates material removal of the specimen surface due to the impact with the steel slag balls. In principle, the mass loss corresponds to the cutting action by the steel slag balls during the shot blasting treatment. The mass loss in the current study increases by the

duration of shot blasting treatment but occurs with a lower rate after 20 min of processing. This finding was also influenced by the enhanced subsurface micro hardness by the duration of the shot blasting. It was well understood that the rate of surface material removal during the impacts with blasting particles decreases by the increasing surface hardness. The high rate of mass reduction during the first 20 min of shot blasting treatment was due to the relatively low subsurface hardness of the specimen. The shot blasting for 20 min yields a harder surface and subsurface layer than those processed with a shorter time. Therefore, a greater resistance against surface material removal was seen for 20 min of shot blasting.

6.2 Further scope of work

Lot of research had been done in the area of Abrasive blasting systems but there are still many opportunities of work in this area which are;

1. Study of Abrasive blasting of different metals and alloys with different abrasives with varying sizes can be a area of further research.
2. Graph theory can be applied to compare different type of Abrasive blasting systems.
3. Optimization of different Abrasive blasting systems with different input is still a vast area of research.

CHAPTER 7

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