Exploring the Abrasive Flow Machining in the Area of Internal Cleaning by Developing a Single Screw Extruder Type Abrasive Flow Machine

Dashrath Sharma [1], S. Jindal [2], M. A. Saloda [3], and Chitranjan Agarwal [4]

[1]M.Tech Student, Mechanical Department, College of Technology and Engineering, MPUAT, Udaipur, India
[2,3]Professor, Mechanical Department, College of Technology and Engineering, MPUAT, Udaipur, India
[4]Assistant Professor, Mechanical Department, College of Technology and Engineering, MPUAT, Udaipur, India

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Abstract - *Abrasive flow machining is the non-conventional machining process used to finish the workpiece internally to get a micro-level finish. The aim of our study to explore the new area of application by design, manufacture, and evaluation of the new system for the cleaning of internal passes. The study is carried out on AFM, how their parameter affects the process. As per our requirement, the design is carried out. The single screw extruder type abrasive flow machining system was designed that is cost-effective and can be operated by the tractor. For the cleaning process, a cost-effective media is used and manually prepared using the mixing of garnet sand as abrasive and SBR or clay as a carrier. The performance of the process is evaluated by using different kinds of media and workpieces. Overall, an effort is made to explore the area of abrasive flow machining application*.

***Key Words*: AFM, Single screw extruder, Internal cleaning, Cost-effective abrasive media, Garnet sand, SBR**

1. INTRODUCTION

In the manufacturing industries, precision in the dimension of a product plays a vital role. There are various methods available for the machining of the product; some of them are conventional and non-conventional. However, in the time of advanced manufacturing, the product used for high speed, heavy load, or high safety requires the exact dimension as per the designed and super finish so that less frictional heat generation in the moving part and slow crack formation on the surface. The creation of the exact external dimension and finish of the object can be achieved by the conventional and non-conventional methods like- turning, grinding, polishing, electrical discharge machining, ECM, etc. but for the internal finishing required a non-conventional finishing process.

Abrasive flow machining (AFM) is a kind of non-traditional technique used for the finishing of difficult to reach an internal area of the product and applied to a wide range of materials like- metals, ceramics, superalloys, etc. Abrasive media is the main element of the AFM process; it is made of viscoelastic polymer reinforced with the abrasive grains. It passes through the workpiece using the hydraulic pressure. This viscoelastic polymer work as a carrier and the abrasive particle work as a cutting tool which removes the microchips from the workpiece. Polymer and abrasive particles are used in different compositions to prepare the media for passing through the kind of products. The cost-effective process always gets appreciation by industries but AFM is costlier than the other finishing process. To improve the material removal rate hybrid AFM is developed by many researchers and this thing motivates us that how to reduce initial cost and running cost, it will become an economical solution for many industries.

As we look into the cleaning process, there are many processes available chemical or non-chemical like grinding, laser, electro-chemical, water jet, etc that are suitable for external cleaning. But for internal cleaning or scale removal required a process that cleans the product internally without damaging and reacting with the product. So the presented work is based on this above mention motivation to develop a mechanism that reduces the cost of abrasive flow machining and applicable to the cleaning of internal passes of the object.

2. LITERATURE SURVEY

Initially, Extrude hone corporation ltd. developed a method of honing by extruding [1]. They create a setup for flowing semisolid to the hollow workpiece and use G.E. silicone putty, isopropyl stearate as a softener, silicone grease for lubricity, and silicon carbide as abrasive for media preparation. They also use another media that constituent the silicon putty, Methyl phenyl silicone fluid, Tetrafluoroethylene powder, and Aluminum oxide. Later develop a new media for AFM; it is the composition of guar gum, boric acid, and borex [2]. In the case study, it is observed that AFM is widely applicable to get predictable and repeatable results in the finishing. It has successfully micro machined the workpiece of different materials ranging from soft Al to tough nickel alloys [3]. The abrasion happens only where the flow is restricted and multi-part can be processed simultaneously with a single fixture.

Abrasive particle work as a tool in the abrasive flow machining process, if the concentration of abrasive grain is increased in the media, the material removal is increased, due to more active grain on the work surface and a large cutting force is observed. If the concentration of the abrasive is further increases from 70 %, not a significant improvement is observed [4]. The active grain density and cutting forces on the work surface depends on the grain size and abrasive concentration. An increase in the grain size and concentration percentage increases the reduction in roughness. An axial force is increased when the increase of pressure but the grain size and abrasive concentration had a negative response. The radial force is increased with the pressure and abrasive concentration but grain size has a negative response [5]. There are commonly used abrasives are aluminum oxide, silicon carbide, boron carbide, and polycrystalline diamond. It is used in 30% to 80% concentration and 100 to 250 nm in mesh size by many researchers

Some of the researchers work on the rheological properties of media and their effect on the AFM process. The viscoelastic material has duel properties of viscous and elastic while flowing. When they add plasticizer for the changing the rheological properties of media. As they observed radial force has intended to penetrate the abrasive particle into the surface and axial force has to indent to shear in axial flow. While increasing shear stress results in increased MR. The media which have a low viscous component pose high material removal because of media content the high elastic component as a result of high radial force [6-7]. The effect of pressure and viscosity on material removal and surface finish is can visualize with the help of the scanning electron microscopy. The major progress in the surface finish of the workpiece happening in the initial few-cycle, and on increasing the pressure and viscosity up to a certain limit; result in the increased material removal [8]. Kind of media is used in AFM like natural rubber, ethylene-propylene-diene monomer (EPDM), polymethylmethacrylate, butyl rubber, silicone rubber, polyethylene (PE), polystyrene, and styrene-butadiene rubber. Many researchers make an effort to develop different abrasive media apart from the commercially existing media. It is observed that developed media are mechanically more stable than commercial media [9] and developed media does not stick with the surface of the workpiece [10]

The material removal (MR) is also dominated by the initial surface roughness and hardness of the workpiece. Harder material has a low material removal as compared to the softer material. The white layer made from WEDM is removed from all specimens by AFM. Initially in the 20 cycles a significant improvement in the roughness later it gradually settled to a saturated level [11-12]. The finishing off the small opening is optimum with a low viscous media and high viscous media is suitable for a large opening [2]. The bell mouthing effect is observed in one way AFM because of the unguided draining of media at the end and getting the faster desire surface finish at the higher pressure. The axial force on the workpiece is increased as increasing in its length and pressure [13]. The researcher used Taguchi to design an experiment using the L_{18} (6^{1}* 3^{7}) mixed orthogonal array for optimizing the abrasive flow machining process parameters and to find the S/N ratio. Analysis of Variance (ANOVA) and F test values used to check the significance of the parameter in the abrasive flow machining [14]. A material model is developed for a visco-elastic abrasive medium. The Maxwell module is used instead of using of standard module for the modeling of media. Shear modules of media assuming a homogenous, isentropic, and low deviating material. Element is used in a parallel format in the generalized Maxwell model. This material model has a separated consideration of the loss modulus and the impact of storage. Later a pragmatic approach is used for the modeling of complex shape workpieces [15-16]. The CFD simulation can help to design workpiece fixtures and to know where AFM is suitable for machining. It is also used to predict the MRR and surface roughness as per the abrasive concentration and size [17]. When the mechanical load is applied, three modes of failure are identified in the thin film as - thickness cracking, interfacial delamination, and interfacial failure. A nano scratch will help to realize the mechanism of abrasive flow machining [18].

Researchers noted that AFM is a slow process because the total time to obtain the required finish is long and the material removal rate is low. To improve the performance of the AFM process many researchers are work on the hybrid machining system in which one or more than one machining process is combined with the AFM to attain the higher surface finish and MRR in less time. In the CFAAFM at a high angular velocity of CFG rod and high pressure improved the quality of surface finish where the large size of abrasive grain and high angular velocity of CFG rod increases the material removal rate (MRR). More than 25 bars of Pressure reduces material removal due to the reduction of the fluidity of media [19]. In the rotational AFM, while the increasing of a rotational speed of a workpiece, the helical path length of abrasive grain increases and helix angle reduce [6]. In the magnetic force assisted AFM, brown super emery (40% ferromagnetic constituents, 15% Si_2O_3, and 45% Al_2O_3) used as abrasive and enhanced material removal is observed when the magnetic field is applied in the region of a workpiece [20]. In the chemo assisted magnetic abrasive flow machining (CMAFM), H_2O_2 is used for the chemical oxidation on the surface. Result in a 79.52% improvement in the surface finish and waviness height of maximum peak reduction by $1/5^{th}$ [21]. In the centrifugal force assisted AFM, introduce the centrifugal force generated (CFG) rod for the rotational of media, they observed that it is possible to enhance the process by improving the fixture and rotation [22-23].

The researcher worked on the cleaning of the types of equipment that are used in the many industries and which factor is affecting the routine of the cleaning like the soil accumulation, corrosion development, the microbial development, thermal properties, impurities, environmental condition, initial surface condition, shape size and age of the equipment. This factor also affects the design of the cleaning system [24-28]. The pipe renewal technique developed by many researchers classified them into three categories:-

Mechanical – rodding, balling, power bucket, etc.
Hydraulic- flushing, jetting, scooter, poly piges, and silt traps, etc.
Chemical- hydroxides, biocides, enzymes, caustics, and neutralizers are used in chemical cleaning [29].

Several methods are used to test the cleanability of the testpiece and different standards are used for comparison depends on the type of element [30]. This literature survey helped in the development of a system for cleaning.

2. Development of screw extruder type abrasive flow machine

2.1 Design

The machine design is based on the input and output parameters. Initially, we plan the machine drive with the electric motor but due to the high cost changed the power system. We operate the machine with help of tractor power ranging from 15 to 45HP with the help of a PTO shaft. So the first consideration starts with the input parameter. In the primary consideration, the machine must sustain or fulfill the following input parameter developed by the tractor in table 1.

Table - 1: Primary design constrain

INPUT PARAMETER	RANGE
Power transmission	0-45HP
Rotational speed	0 – 150 RPM
Vibration and jerk	N/A
PTO type	6 spline, 540 RPM

There are some of the other parameters are kept in the consideration which also affects the design constrain- Wear, Heat dissipation, Lifespan, (Maintenance, repair, and overhaul) MRO, Installation and uninstallation, Working condition, etc. design work is carried out using the student version of Solidworks modeling software available in the mechanical department of CTAE, Udaipur. There is a right-handed screw used to puss the media instead of hydraulic cylinders because it is cost-effective and it can flow a large amount of mass. Bearing housing also a crucial part of the machine as it holds the screw and transfers the power. A standard roller bearing is used as shown in figure1.

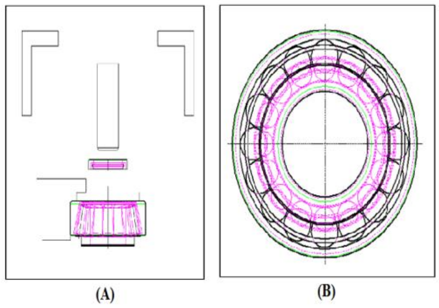

Fig-1: Concept of bearing housing (A) Top view (B) Front view

As per the obtained constrain, all parts of the machine are designed and assembled in the software as shown in figure 2.

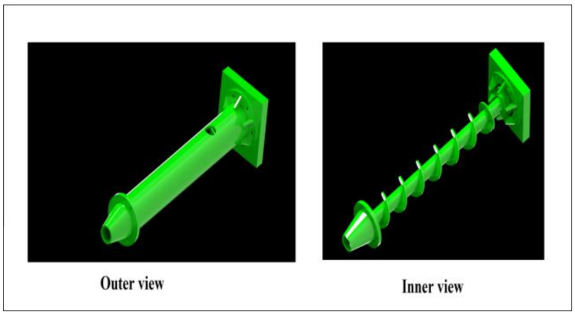

Fig-2: Assembled view of a machine

2.2 Manufacturing

This machine is funded by the New-Gen IEDC CTAE, Udaipur, and manufacture on a tender basis. Fabrication is carried out at Shoolin Mechatronics Pvt. Ltd., G-1, 469 Madri Industrial Area, Udaipur, India. Approx all designed parts fabricated from mild steel. The standard parts are purchased directly from original manufacturers. Cylindrical parts are manufactured from pipes of high thickness. The threads of the screw and reducer are made of plain thick sheets of metal. For the fixturing, attachable flanges of different sizes are directly purchased and based on the size of the pipe to be clean.

3. Testing procedure

For the performance evaluation of a single screw extruder type - an abrasive flow machine and to know the effect of the parameters on the processing test is carried out on the normal days. There are the following step is to be followed in the testing procedure.

3.1 Installation

In the Installation, a priority is given to the safety of people, machines, and tractor. Initially, we installed the machine and check the alignment and then install the fixture and workpiece. Installed the machine onto the tractor using the H crane available in the industry. Using the iron chain ties the machine from two places one from the middle and another from the front. Connect the middle chain with the crane and hold manually from the front then bring it close to the PTO. Don't move fast while attaching the machine with a tractor, slowly rotate the PTO grooves and move the coupling of the machine into the PTO shaft of the tractor. Latter fix the machine on the tractor by 12 fasteners so that it bears jerk and torque developed during the processing. After checked the alignment of rotating and non-rotating parts by a trial run. During the installation of the fixture first, attach the workpiece with the fixture so that tread does not damage, and then attach the fixture with a machine, use a seal, and fasteners with wisher so that the media does not leak while running at high pressure. Any leakage will be harmful because there is the development of hot gases and vapor during the processing.

Fig-3: Installation of the machine

3.2 Preparation of media and workpiece for testing

Media preparation is an important part of AFM; ideal media have good rheological properties as result in less time of finishing and good surface finish. But in actual condition media preparation is based on the application. A cost-effective Garnet sand is used, it has a hardness of 7.5 Mohs and general chemical composition of $A_3B_2Si_3O_{12}$, here A for divalent cation (Ca^{2+}, Fe^{2+}, Mn^{2+}, Mg^{2+}), and B for trivalent cation (Al^{3+}, Fe^{3+}, Cr^{3+}). The calculation of the percentage concentration of abrasive in the media is getting by equation 1.

Percentage concentration of abrasive particle =

$$\frac{\text{weight of abrasive}}{\text{weight of abrasive+weight of carrier}} \times 100 \qquad 1$$

Preparation of (Clay + Garnet sand) media- we bring dry clay from the agricultural field and removes the stone and other elements using a sieve of fine mesh. Then mix the composition of the clay and fine mesh garnet sand in a different ratio. Later add the water and mix to make the media viscous like mud.

Fig-4: (Clay + Garnet sand) media preparation

Preparation of (SBR + Garnet sand) media- Styrene-butadiene rubber polymer is available in the sheet form so we cut it in a small piece using a special cutting tool manually. We segregate the Garnet sand in the different mesh sizes using sieves. Then mix the abrasive with the polymer in a particular ratio. Later adding diesel for softening the SBR and put the mixture for two days. We test the softening capability of SBR as shown in figure 5(a). Before using in the processing, we passed the media in the extruder without the workpiece so that it mixes well.

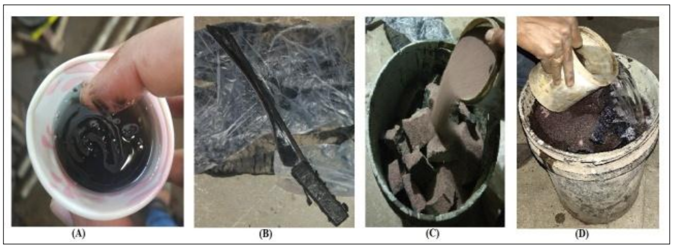

Fig-5: (A) Softening pretest of SBR (B) SBR cutting knife (C) Mixing of SBR and Garnet & (D) Addition of diesel in the mixer of SBR and Garnet sand

Preparation of workpiece- for the test a rusted pipe is used as shown in figure 6, instead of a special clamping fixture a cost-effective flange is used so the workpiece is required to prepare for attaching with flange by treading on the external surface of pipes.

Fig-6: Testpiece

3.3 Drive the machine

After the installation of the machine, use a stopper for the tractor in case of emergency it doesn't harm. Then start the tractor while putting the gear on neutral, now using the PTO gear start to drive PTO. Take the rotational speed of the PTO and compare the speed with the speedometer of the tractor as they are proportional to each other. When the speed comes at a constant level, start the finishing process by feeding.

3.4 Processing

Start the media feeding manually in the hopper and keep the other parameter constant. If the media do not mix well, screw mixed it properly during the extrusion process. Later the workpiece of different sizes and different media is used for finishing operations. Use gloves while feeding and keep hands away from the screw.

Fig-7: Processing on (A) 1-inch testpiece with clay and garnet media (B) 2-inch workpiece with clay and garnet media (C) 2-inch workpiece with SBR and garnet sand media

3.5 End results

After the processing, detach the workpiece and noted down the performance characteristics and result parameter for the evaluation of a machine.

Fig-8: End result of an internal surface of pipe treated with; (A) Clay and Garnet media, (B) SBR and Garnet media

3.6 Uninstallation and Cleaning of the machine

After the operation, it is required to clean the machine, otherwise next time, in the operation several problems occur like choking, vibration, noise, heating, etc. As all the process is done we uninstalled the machine and put it on the stand as shown in the figure.

Fig-9: Machine after testing

4. Result and discussion

In this section, we talk about the performance evaluation of the single screw type abrasive flow machine. A comparative analysis of the parameters like type of media, abrasive concentration, size of workpiece, rotational speed, etc. is carried out. The test is performed using the John Deere 5310 tractor. Initially, the media is prepared and then the machine is set up on the tractor, later a test run is performed on the test piece of size 1, 1.5, 2 inches in diameter, and length of 30.48 cm. The following performance characteristics are observed throughout the test run.

4.1 Carrier

In this process, two class of carrier is used one is clay and the second is SBR When the media is prepared with the same abrasive grain size and percentage of concentration. The test is carried out on the same size and shape of pipes cut down from long rusted pipe made of steel so that each testpiece have the same internal structure of the surface. The test results that observed using different carrier are shown below in figure 4.1. There are media 1 contain the dry clay and garnet sand in the ratio of 40:60 by weight and the media 2 contains SBR and garnet sand in the same ratio. Where the water is mix in the media 1 with 30% of total weight and 10% diesel in media 2 to make viscous.

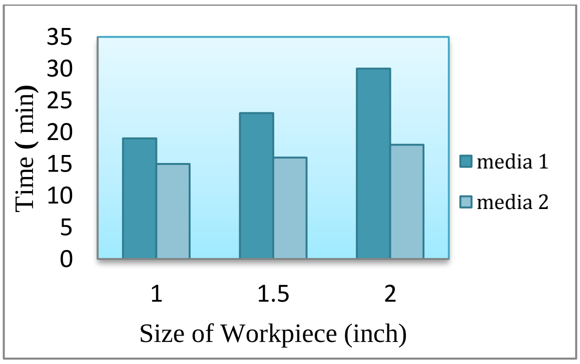

Chart-1: Effect of the carrier on the cleaning of rusted pipe with different diameter

We examined that when SBR media is employed in the processing, the time required for cleaning is less than clay media even tested with the same size of the testpiece. Machining time depends on the dimension of the workpiece, if we use the small size workpiece for cleaning; the time required is less due to increased pressure and flow rate in the workpiece even when operated with the same angular speed.

4.2 Flow rate

In the processing, the flow rate depending on the many factors where the effect of concentration is observed shown in the graph below while the keeping independent parameter constant.

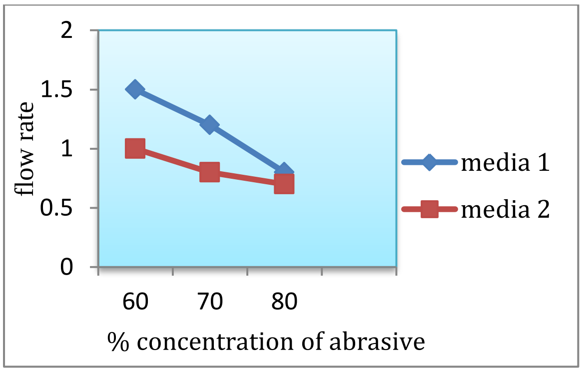

Chart-2: Effect of abrasive concentration on the flow rate

As shown in the chart flow rate is reduces on increasing percentage concentration of abrasive grain and the drop in the flow rate of the clay media is more than the SBR media. The high concentration of abrasive grain in the media will develop higher resistance as a result of the low down of flow rate in the same workpiece. If we further increase the abrasive grain in the clay media the flow rate reduces to zero, the media choked in the reducer due to very less rheological properties in the media. As on choking, the temperature is increasing rapidly due to the conversion of mechanical energy into the heat result in vapor and gas development from the media.

4.3 Abrasive concentration

The effect of abrasive grain concentration in the media is observed on the cleaning of a 2-inch rusted pipe of the same length 30cm. The result is shown in figure 4.3.

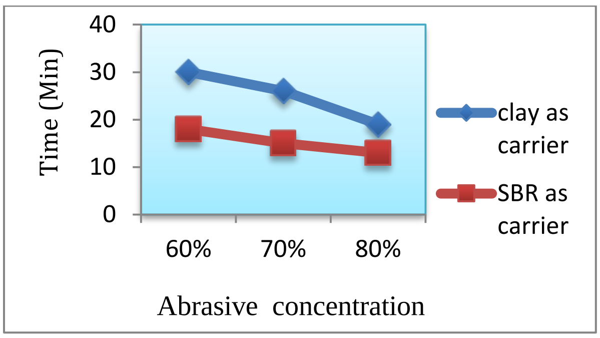

Chart-3: Relation between the abrasive concentration of the media and processing time

As shown in the chart, increasing the abrasive grain percentage in the media is improving the material removal rate due to the increasing of abrasive particles on the surface of the test piece result in less time is required to remove rust. But on increasing the concentration reduces the flow rate, depending on the capacity of the machine, so at the very higher concentration, the required time will be more.

4.4 Fuel consumption and cost estimation

As we operated the tractor at a steady speed as the fuel consumption and cost are directly proportional to the total time required for the cleaning. The average consumption of the diesel on the john deere 5310 is observed 7 liters/hour while running at avg. 110 rpm during the processing. The result of fuel consumption for different sizes of pipes is shown in chart 4.

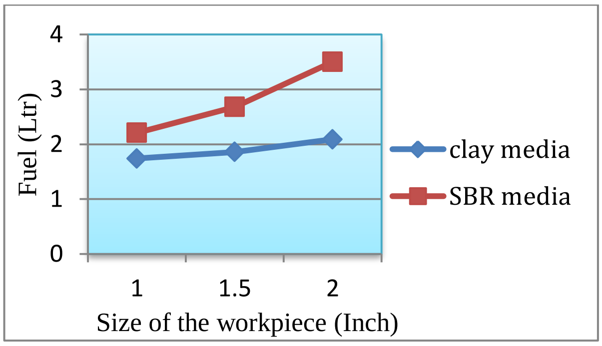

Chart- 4: Fuel consumption of cleaning

The large-size workpieces take more time to finish as a result of the high consumption of fuel. While the processing with SBR media consumes less fuel as compared with clay media. The running cost with the SBR media is low due to less fuel consumption but the primary cost of media is high. The media is reusable so it can be applied multiple times. The initially required media depend on the size of the machine, workpiece, and the feeding mechanism. We calculate the cost of finishing a testpiece of size 2-inch diameter and 30cm length considering the estimated cost of the media element is shown in table 2.

Table 2: Estimate cost of a media element

Minimum estimate Requirement	Rate	Total amount
Garnet abrasive sand (10 kg)	15 □/kg	150
SBR (8kg)	55 □/kg	440
Diesel (2ltr)	80 □/liter	160

So the initial cost with the SBR media is 750 ⍰ excluding labor and transportation cost while the initial cost with clay media was only 150 ⍰ of abrasive (10kg) when excluding another minor cost. The running cost for the single piece treated with clay media is 350 ⍰ and with SBR 210 ⍰ on considering the market price of tractor rent at 700 ⍰/hour. Where the fabrication cost of the machine is bided at a price of 78000 ⍰. When we compare the process with SBR and clay media, finishing with SBR media is cost-effective when it is reused on more than four testpieces as shown in chart 5.

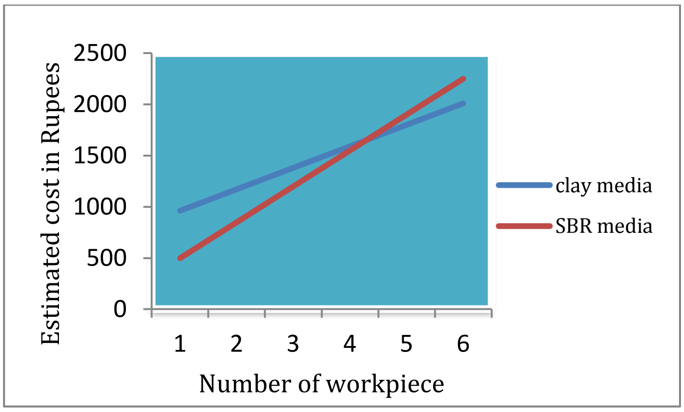

Chart -5: Cost of cleaning with different media

4.5 Surface improvement

There are testing is performed onto the rusted pipe, the surface condition of the workpiece was initially in very bad condition due to the layer formation of corrosion sediment, salt vegetable, chemical, etc. While applying the AFM with a different media on the workpiece the result are symmetric and higher improvement is observed with SBR. When treated with clay media it removes all layers but in the deep small hole, made due to defects in the surface, does not clean even fill it with clay. The color of clay media became the same as iron corrosion during the process so it is visible like corrosion. When treated with the SBR media result are observed well as compare with clay media. It is also observed that SBR media after removal of rust start removing material of workpiece while clay media does not significantly remove metal due to very little elasticity. The surface becomes smoother with SBR media, it improved surface roughness by plastic deformation and removal of surface roughness peal.

5. CONCLUSION

Initially, we studied about Abrasive flow machining process and the effect of their parameter; we found that a lot of work is carried out on it. Many researchers work on the modeling of the process but none of them get significant outcomes due to the modeling is depended on the hypothesis. The people also work on the enhancement of AFM using different techniques and they get significant improvement in the process. But the application area does not significantly explore so we studied and observed that abrasive flow machining has the potential to apply in the cleaning process of complex parts.

The designing of the abrasive flow cleaning system is carried out using the mechanism of a screw extruder instead of a hydraulic cylindrical system because the cleaning system must require a cost-effective machine. So we design a right-handed single-screw extruder type AFM system and instead of an electric motor, we use a tractor so that the manufacturing cost will minimize. The industrial media is used in the AFM is costlier so we used manually prepared cost-effective media for the cleaning, garnet sand is used as abrasive and SBR or clay used as a carrier. The developed machine is tested on the rusted pipe using the prepared media. As we found that SBR media poses a good result instead of the clay media. The material removal is increased by increasing the concentration of abrasive and the size of abrasive grain in the media. Material removal can be increased by increasing the flow or pressure in passes with the help of a tractor. The required time of cleaning also depends on the size of the workpiece. If the length of the pipe increases the flow is reduced and the required pressure will become high to flow media in the pipe. After the various testing of AFM on different sizes of a workpiece using the media of different compositions, we come up with the conclusion that a single screw extruder type abrasive flow machine can be used to removing the scale, rust, corrosion, etc. from the complex workpieces. A cost-effective extruder has less control over the parameter and also less variability so the size of the screw depends on the objects that to be clean. In this type of machine, more heat is generated compared to a commercially available machine so the more thermally stable media is suitable for it. Using the AFM we can clean a different type of internal surfaces also it is useful to remove the coating on the surface like paint, corrosive resistant coating, etc. This research will help to explore a new area of AFM applications.

5.1. Suggestion for future work

With the help of this study, some suggestion is recommended those are useful for the researcher to use in the future to enhance and improve the machining process, reduce the cost, and applied on a wide range of products given in the following points:

- This process can be applied to the cleaning of the complex parts, on the different types of rusted surfaces, in the microfluidics, in the coating removal, etc.
- This type of Abrasive flow machining (AFM) system can be used for the finishing of a product that is made of soft materials like silver, gold, brass, Al, etc.

- As we observe that the screw is super finished as the use of abrasive media so any parts can finish internal or outer by rotating in the abrasive viscous media.
- The heat production is high in the screw so an effort can be made to increase heat dissipation and develop media that sustain high temperatures and cost-effective.
- Commercially available abrasive flow machines can be used for the cleaning of complex parts.
- For the complex object, a magnetic field can be used for the clean the hidden area by using abrasive of magnetic character.
- Garnet sand is also partially magnetic in character so this abrasive can be used in magnetic force assisted abrasive flow machining for enhancement of material removal.

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BIOGRAPHIES

M.Tech Student, Department of Mechanical, CTAE

Professor and Head of the Mechanical Department, CTAE

Professor, Department of Mechanical, CTAE

Assistant Professor, Department of Mechanical, CTAE