JANUARY, 2014 **Ph.D. in Mechanical Engineering** **KÜRŞAD GÖV**

UNIVERSITY OF GAZİANTEP

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ABRASIVE FLOW MACHINING OF EDMed SURFACES

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MECHANICAL ENGINEERING

BY

KÜRŞAD GÖV

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Abrasive Flow Machining of EDMed Surfaces

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Supervisor

Prof. Dr. Ömer Eyercioğlu

By

Kürşad GÖV

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Kürşad GÖV

ABSTRACT

ABRASIVE FLOW MACHINING OF EDMed SURFACES

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Abrasive flow machining (AFM) is a novel technique having potential to provide high precision and economical means of finishing inaccessible areas and complex internal passages of hard, high strength, heat resistant alloys and die steels. The AFM process has been applied to improve the surface integrity of the parts processed by electro-discharge machining (EDM). During EDM process, rapid heating and cooling occur and they cause re-cast (white) layer which has micro-cracks, poor mechanical properties and irregular features on the workpiece surface. The effects of AFM process parameters (number of cycles, abrasive type, mesh size and concentration, workpiece material and hardness) on wire EDMed surfaces have been investigated in this study. A one-way and two-way machines were designed and constructed to carry out the experimental work. A polymer based abrasive media which acts as a deformable grinding tool for obtaining enhanced quality characteristics has been developed. A series of experimental studies were carried out on DIN 1.2379 cold work tool steel and titanium (grade 1) using SiC, Al_2O_3, B_4C and garnet as abrasives with different mesh sizes and concentrations. The experimental results showed that the white layer formed during WEDM is successfully removed by AFM in a few cycles and the surface roughness of the rough-cut samples reaches to the finish-cut ones. Therefore, the pre-machining time and the cost may be reduced by eliminating finish cut in WEDM, if AFM is used as the post-finishing process. The surface roughness decreases with increasing number of cycles and the abrasive concentration. The resulting R_a values are comparable to the surface quality of those obtained from lapping and super-finishing. The material removal increases with increasing abrasive mesh size and the abrasive hardness. The experimental results also showed that the harder workpiece material has more surface improvement than the softer ones.

Key Words: Abrasive Flow Machining AFM, EDM, Surface Finishing

ÖZ

AŞINDIRICI MACUNLA ELEKTRO EROZYON YÜZEYİNİN İŞLENMESİ

GÖV, Kürşad

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Aşındırıcı macun ile işleme (AMİ) ulaşılması güç, karmaşık şekilli, sert, mukavemeti yüksek, ısıya dirençli alaşımların ve kalıp çeliklerinin ekonomik ve yüksek hassasiyetli işlenmesinde kullanılan yeni bir yüzey bitirme metodudur. AMİ metodu elektriksel erozyon (EDM) ile işlenmiş parçaların yüzey kalitesinin iyileştirilmesinde kullanılmaktadır. EDM işlemi esnasında, yüksek ısı ve hızlı soğumanın etkisi ile parça yüzeyinde beyaz katman tabakası oluşmaktadır. AMİ metodu sonunda, mikro çatlakların sebep olduğu düşük mekanik özelliklere sahip bu katman yüzeyden kaldırılarak yüzey kalitesi iyileştirilmektedir. Bu çalışmada, AMİ işlem parametrelerinin (döngü sayısı, aşındırıcı tipi, aşındırıcı tane büyüklüğü ve oranı, iş parçası malzemesi ve sertliği) tel erozyon yüzeyine etkileri araştırılmıştır. Deneysel çalışmaların gerçekleştirilmesi için bir tek-yönlü ve bir de iki-yönlü AMİ makinası tasarlanmış ve imal edilmiştir. Yüksek kalite özelliklerini elde etmek için esnek taşlama takımı gibi davranan polimer esaslı aşındırıcı bir macun geliştirilmiştir. Soğuk takım iş çeliği DIN 1.2379 ve titanyum (Grade 1) malzemeleri kullanılarak deneysel çalışmalar gerçekleştirilmiştir. Deneylerde SiC, Al_2O_3, B_4C ve Garnet, aşındırıcı olarak değişik tane büyüklüklerinde ve oranlarında kullanılmıştır. Deney sonuçları, tel erozyon esnasında oluşan beyaz katman tabakasının AMİ yöntemiyle birkaç döngüde tamamen kaldırıldığını ve kaba-kesim yüzey pürüzlülük değerinin bitirme seviyesine ulaştığını göstermiştir. AMİ işleminin son bitirme işlemi olarak kullanılması halinde, tel erozyonda bitirme işlemini ortadan kalkmasıyla ön işleme zamanı ve maliyeti azaltılabilir. Yüzey pürüzlülük değeri döngü sayısının ve aşındırıcı oranının artmasıyla azalmaktadır. Elde edilen R_a değeri lepleme ve süper-bitirme metotlarıyla mukayese edilecek düzeydedir. Malzeme kaldırma, aşındırıcı tane büyüklüğü ve sertliğinin artmasıyla artmaktadır. Ayrıca deneysel çalışmalarda, sert iş parçasının yumuşak olanlara göre daha iyi yüzey kalitesine ulaştığı görülmüştür.

Anahtar Kelimeler: Aşındırıcı Macunla İşleme, EDM, Yüzey Bitirme

To my wife, son and daughter
Sabiha, İbrahim and Selvi

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AFF	Abrasive Flow Finishing
AFM	Abrasive Flow Machining
EDM	Electric Discharge Machining
MR	Material Removal
MRR	Material Removal Rate
MAFM	Magneto-Abrasive Flow Machine
MRAFF	Magneto-Rheological Abrasive Flow Finishing
MRPF	Magneto-Rheological Polishing Fluid
NTD	Non-Traditional Machining
$\mathbf{R_a}$	Surface Roughness µm (arithmetic average)
$\mathbf{\Delta R_a}$	Change in Surface Roughness
$\mathbf{R_t}$	Surface Roughness µm (maximum height)
$\mathbf{R_q}$	Surface Roughness µm (root mean squared)
SEM	Scanning Electron Microscope
WEDM	Wire Electric Discharge Machining
WLT	White layer thickness

CHAPTER 1

INTRODUCTION

1.1 Introduction

Manufacturing industry is becoming ever more time and quality conscious with regard to the global competition, and the need to use complicated and perfect components having some special shape requirements. The demand for materials made from exotic, high strength and temperature resistive materials, tool and die steels and advanced materials are growing day by day. These materials find particular use in modern manufacturing industries, especially, in aerospace, automotive, tooling, mould and die making industries. Higher costs essential to the machining of these materials besides difficult design requirements, which include precision machining of complex and complicated shapes and sizes, finishing of inaccessible areas at micro levels with tight tolerances are the major limitations which have led to the development of newer advanced non-traditional machining processes. Alternative approaches have been attempted on the use of new and advanced technologies for quickly turning raw materials into usable goods.

Hence, non-traditional machining methods including electrochemical machining, ultrasonic machining, electrical discharging machine (EDM) etc. are applied to machine such difficult to machine materials.

The basic principle behind EDM process is a series of electric sparks between the workpiece and wire electrode. During EDM process, rapid heating and cooling occur and they cause a heat affected layer on the machined surface. This layer is generally formed by the sticking of the non-removed debris and also the depth of material affected from high temperature. The top of the layer consists of re-solidified layer and has re-cast structure.

The recast layer seems white colour on microscope and thus it is commonly referred to as the white layer. The white layer is very hard and brittle and has micro-cracks [1-3].

The conventional finishing processes, in spite of recent technical advancements, are inadequate to finish complex shapes in hard, high strength alloys and die-mould steels. Keeping these requirements in mind, a number of Non-traditional finishing (NTF) processes have been developed. Abrasive flow machining (AFM) is one of the Non-traditional finishing (NTF) processes. Abrasive flow machining (AFM) is a novel technique having potential to provide high precision and economical means of finishing inaccessible areas, complex internal and external passages.

AFM process has been applied to improve the surface quality of the workpiece machined by EDM. The surface roughness of workpiece could be reduced significantly using abrasive based media. The surface finish improvement is about 90 % [3]. The undesired recast layer, which has poor mechanical properties and irregular features, was eventually removed by AFM process.

Abrasive Flow Machining was developed for the abrading of aircraft valve bodies and grew up in the 1960's [4], AFM is a process in which a polymer based carrier mixed with abrasive particles is extruded under pressure back and forth through or around a workpiece surface. Since its creation, AFM has been used to polish, clean, deburr, produce radius edge on components and the removal of recast layers of the components where conventional machining is not possible.

The present research initiative identifies the limitations and gaps through an exhaustive review of published literature on AFM technique with the intent to explore the possibilities for improving the efficiency and capabilities of the AFM process on EDMed surfaces. Very few research studies have been conducted on the EDMed surfaces that finished by AFM. Therefore, a need appears to study the AFM process on EDMed surfaces to get more comprehension into the real interaction between the abrasive flow machining process parameters and the target surfaces.

Experimental investigations have been performed on the two types of AFM machines that were designed and developed during the study for variation in process parameters to facilitate the parametric study for the evaluation of the process. A polymer based abrasive media which acts as a deformable grinding tool for obtaining enhanced quality characteristics has been developed.

Identification of all the possible AFM process parameters that may influence the capability and efficiency of the process, investigating the behaviour of these process parameters, and investigation of the workable range and the levels of AFM process parameters has been obtained on the basis of results from the preliminary experiment and the limitations imposed by AFM machines. The input parameters selected for the present investigation can be classified to three groups; AFM process parameters, abrasive media parameters and workpiece parameters. The AFM process parameters are; number of cycles, extrusion media pressure, media flow speed, and machining time. The abrasive media parameters are; media viscosity, abrasive type, abrasive mesh size and its concentration. The workpiece parameters are mainly; the type of workpiece material (metallic and non-metallic etc.), the shape of workpiece, hardness of the workpiece, and the pre-machining process of workpiece. The output parameters are selected as surface roughness and material removal (MR), of the finished workpiece surfaces. Scanning electron microscope (SEM) images and optic microscope images at the surfaces were investigated.

1.2 Statement of the Problem

The main goals of AFM process are to achieve better stability and higher productivity, for example, higher finishing rate with the desired accuracy and surface quality, and minimum machining time. However, due to a large number of variables and the complex nature of the process, even a highly skilled operator working with a state-of-the-art AFM is unable to achieve consistently optimal physical and economic performance. As a result, machine parameters are regularly changed to compensate for variations in the process, and the media batch is replaced on a conservative schedule [5].

Although abrasive media have some kind of limitations, selecting optimal viscosity, abrasive types and mesh sizes is still an extremely difficult job. The lack of machinability data on all abrasive media/material combinations are the main difficulties towards achieving AFM process for a large number of applications [5].

Presently, there is a lack of published literature on the AFM process characteristics, workpiece hardness, abrasive types and subsurface characteristics. However empirical evidence based on limited experiments, provides some preliminary information about the effects of certain process parameters. Although these results provide valuable insight, more detailed studies are needed to lay the foundation for examining the effect of the parameters on the AFM process [6].

1.3 Aim of the Thesis

The aim of this PhD is to gain a better understanding of the abrasive flow machining process parameters such as number of cycles, media concentration, abrasive types, and abrasive mesh size, when used as a finishing process.

This will be achieved through a combination of experimental investigation techniques. The research conducted within this thesis will benefit both the academic and industrial communities by presenting data and operating parameter relationships to enable the abrasive flow machining of EDMed surfaces.

To sum up, the objectives of the present research initiative are detailed as following stages:

1. Development of AFM machine, which facilitates provision for variable AFM process parameters in finishing different workpiece.
2. Development of polymer based abrasive media and selection of its type, size and composition which yields enhanced quality characteristics.
3. Examination of the effects of the AFM process parameters on the EDMed workpiece surface.

The present research initiative has been conducted in a staged manner towards accomplishment of objectives and the different phases have been described as follow:

Stage 1

- Development of AFM machines, which have been designed and indigenously fabricated by the author and providing the provision for variation in process parameters.
- A one-way and a two-way AF machines were designed and manufactured, also a heating-cooling unit was connected to the system.

Stage 2

- Having developed and installed the AFM machines, the next crucial step of our study was the development of polymer based abrasive media which acts as a deformable grinding tool and its composition in order to obtain enhanced quality characteristics and improved efficiency and process capabilities.

Stage 3

- Identification of all the possible AFM process parameters that may influence the capability and efficiency of the process and investigating the behaviour of these process parameters by conducting preliminary experiments.
- Investigation of the workable range and the levels of the AFM process parameters based on the results obtained from the pilot experiments and limitations imposed by our AF machines.
- Identification of the output response which truly reflected the performance measures of the AFM process, Material Removal (MR) and Surface Roughness (R_a) have been selected as the quality characteristics as performance indicators, respectively.
- Identification of viable live industrial components which could be used as work-pieces in the present study, with the perspective of studying the feasibility of integration of this technique with today's small scale industries.

1.4 Organization of the Thesis

This thesis is composed of seven chapters. The statement of the problem and the objectives are defined in Chapter 1.Chapter 2 contains a literature review of the AFM process. This section also highlights the current research of AFM. From the literature review, knowledge gaps are identified in the field of AFM. Chapter 3 outlines the history of abrasive flow machining, and uses within the manufacturing industry, mechanisms, parameters, tooling, control systems and developments. Chapter 4 gives details with the design and manufacture of the two AFM machines specifically to conduct the experimental work in this thesis. The capabilities of the machines are identified in this chapter through a series of preliminary experiments. Chapter 5 consists of the experiments performed. Experimental procedures are given in this chapter, and an introduction is given to the equipment and instrumentation used.

Chapter 6 presents the experimental results and analysis of the work conducted to determine the effects of the machining parameters outlined in the methodology. A discussion of the work conducted is presented in detail about the effects of machining parameters on the workpiece surface finish, geometry and material removal rate. The main conclusions drawn from the thesis and the future recommendations are given in Chapter 7.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

Abrasive flow machining (AFM) is a material removal process by a viscous polymer based abrasive media that is flowing through a workpiece passage or surface under desired media pressure. Commonly, the polymer based abrasive media is flowed over internal or external surfaces of the workpiece with unidirectional reciprocating motion.

The characteristic of the polymer based abrasive media has significant effects on AFM process. It is dependent upon the main parameters, such as media viscosity, extrusion pressure and temperature. Four types of abrasives are commonly used in polymer based abrasive media for AFM process, such as silicon carbide SiC, aluminium oxide Al_2O_3, boron carbide B_4C and diamonds.

The success of the AFM process depends on number of process parameters that can be classified in three groups; AFM parameters, abrasive media parameters and workpiece parameters, respectively. The AFM parameters are pressure, flow speed, number of cycles and machining time. The abrasive media parameters are viscosity, temperature, abrasive type, mesh size and its concentration. The workpiece parameters are mainly the shape, the workpiece hardness, the pre-machining condition and surface texture.

This chapter is divided to five sections. The studies on AFM process parameters and modelling of these parameters are given in Sections 2.2 and 2.3, respectively. In section 2.4, the previous works on AFM media parameters are reviewed. The studies on workpiece parameters are presented in Section 2.5. The various finishing processes which were developed from AFM are outlined in Section 2.6.

2.2 AFM Process Parameters

Abrasive Flow Machining (AFM) process was developed in 1960's but started to be used widely in industry as early as in the seventies [7, 8]. The AFM taken place the traditional finishing process which had many limitations. It filled technological gap in production of components of complex shape, having important and not easily accessible surfaces or edges. It has become preferable for non-traditional finishing processes in specific manufacturing industries such as aerospace, automotive, die and mould industries, etc. Technological requirements have directed the types of AFM machines and process parameters. Experimental studies have been carried out by various researchers to investigate the effects of AFM process parameters such as number of cycles, extrusion pressure, media viscosity, abrasive type, size and concentration on the output responses namely, surface roughness and material removal (MR) during AFM.

To understand the fundamentals of AFM process [6, 9], some studies have been done. Przyklenk [10] reported the detailed results of experimental work concerning the effects of AFM process parameters on surface roughness, material removal (MR) and radiusing edges in different workpieces. Loveless *et al.* [11] presented the textures of the surfaces which were finished by AFM process by using scanning electron microscopy (SEM). Jain and Adsul [12] also presented SEM photographs of surfaces that were finished by AFM process, acquired under different AFM process conditions. Rhoades [13-15] carried out an experimental study to investigate the fundamental principles of AFM process and determined its main parameters. He observed that when the media was suddenly forced through restrictive passage (its viscosity suddenly rose). High material removal was achieved only when the media viscosity was high. The success of the AFM process depends on tooling, extrusion pressure, media viscosity and media flow volume. All these parameters finally change the number of particles interacting with both the workpiece and abrasive grain. A higher volume of media flow increases number of abrasive grains interacting with the workpiece, therefore more abrasion takes place. Number of cycles depends on the velocity of media, during a given time period. Flow pattern of media depends on its out-flow speed, media rheology and passage size. AFM can be used in industrial applications such as precision deburring, edge contouring, surface finish, removal of recast layers, etc. [16].

Davies and Fletcher [17] presented a relationship between the number of cycles, pressure and temperature drop across the die for the type of polymer and abrasive concentration. Increase in temperature of media results in a decrease in media viscosity and an increase in the flow rate. As the number of cycle increases, media temperature increases by causing a change in the media viscosity. They reported that a rise in temperature is due to a combination of internal shearing of the media and finishing action of the abrasive grit.

Williams *et al.* [18] carried out an experimental study and qualitative analysis to investigate the amount of material removal in AFM process. He also reported surface roughness characteristics and material removal due to number of cycles for a single hole on workpiece and found that the most evident change in the bore diameter and surface roughness occurred on the first cycle.

Uhlmann and Szulczynski [19] presented that a nonlinear relationship exists among number of cycles, pressure and efficiency. They proved this relationship based on an experimental study. Such high pressure of forcing viscous elastic media through holes and slots of various cross-sections significantly changes the condition of flow due to different friction forces. This results in a local rise of media temperature and subsequently the viscosity and efficiency of the media to decrease. Therefore, additional units have to be established to cool down the workpiece. A media of low viscosity can not be applied in conventional AFM because of their limited abrasive machinability.

Singh [20] reported that some comparative studies between AFM and other finishing processes. The simultaneous increase in both MR and Δ R_a indicates the unique behaviour of AFM in comparision with other machining processes and these results verified those reported by Williams and Rajurkar [21]. One possible reason could be that, in AFM, the material removal takes place first from hills or peaks of the surface profile. More material removal produces a smoother surface. In other words, the more material removal the smaller is the height of hills on the surface, and hence the lesser is the roughness of the surface. This holds good until all of the high hills are removed and quite a smooth surface is produced.

Gorana *et al.* [22] studied the effects of the AFM process parameters on output performance parameters such as improvement in surface roughness (ΔR_a), material removal (MR), active grid density and cutting forces. They developed set up for measuring radial and axial forces during AFM process, and reported that higher percentage reduction in surface roughness was achieved for 80 to 220 mesh sizes, beyond 180 mesh size, the behaviour of ΔR_a became irregular, and indicated a linear relationship between the extrusion pressure and ΔR_a. Additionally, they showed the some process parameters such as abrasive concentration, abrasive grain size and extrusion pressure have beneficially effects on the performance parameter of ΔR_a. Jain and Jain [23] these supporting results reporting that the ΔR_a increases with increase in abrasive concentration and media extrusion pressure. However, they observed that ΔR_a was higher with increase in abrasive mesh size. Williams and Rajurkar [84] also reported that abrasive grain size and media extrusion pressure had significant effects on AFM process.

Hsinn-Jyh Tzeng [24] reported the results of experimental work, using the Taguchi method, concerning with the effects of AFM parameters on the micro slits of biomedicine workpiece. The process parameters were taken as abrasive mesh size, concentration, extrusion pressure and machining time effect on the dimensional accuracy of the micro slit manufactured by WEDM. Results were also explained by using a scanning electron microscope (SEM).

Some researchers have studied on the characteristics of AFMed surfaces. Haan *et al.* [9] studied the effects of AFM parameters on surface finishing and showed that AFM introduced a wide variation of material removal rate with several levels of the machining parameters.

AFM is an effective method to deburr, polish and remove the white layers formed by wire electrical discharge machining (WEDM) [11, 25]. When the complex hole geometry is polished, the surface accuracy can be controlled by changing the AFM parameters such as abrasive mesh size, abrasive concentration, number of cycles and media flow speed [12]. Media extrusion pressure and media viscosity significantly affect the material removal (MR) and surface roughness (R_a) [6].

Fang *et al.* [26] presented that AFM process has generally two kinds of particle movement patterns such as rolling and sliding/rubbing. These modes affect the AFM process by interacting both the workpiece and abrasive particles and they are related to the polishing, buffing and burring efficiency. These modes also shape the micro-chip formation, ridge formation and low-cycle fatigue wear. They concluded that particle movement patterns are significant parameters for the finishing efficiency in AFM process.

Mali and Manna [27] reviewed the current status of AFM and observed that number of cycles, media extrusion pressure, abrasive mesh size, media flow rate, and the workpiece conditions are the significant AFM process parameters that affect the surface finish quality. They developed a hybrid AFM processes by combining the abrasive flow finishing (AFF) with other non-traditional processes.

2.3 Modelling of AFM Process

Many researchers have proposed some experimental and mathematical models for AFM process.

Analytical models have difficulties in explaining a highly non-linear relationship with interactions among process variables. Moreover, there are no analytical model that capture the dynamics of the entire abrasive flow machining process. Artificial intelligence techniques, such as neural networks and expert systems, have been used successfully to model the process behaviour in the areas where analytical models cannot be developed. The use of neural networks is motivated because of their accommodation of non-linarites, interactions, and multiple variables. Neural networks are also tolerant of noisy data and can operate very quickly in software, and in real time in hardware. Unlike statistical models which generally require assumptions about the parametric nature of the factors, neural networks do not require apriority assumption of the functional form of the model.

Abrasive flow finishing (AFF) process modelling has been done by using genetic algorithms and neural networks [28]. The neural network model is successful to predict the surface roughness and material removal rate MRR in AFM process [29]. And cascade correlation neural network approach is also a better method compared to the back propagation technique [30].

The prediction of dimensional accuracy and surface roughness and development of modelling of AFM process were studied by Petri *et al.* [31]. Selecting optimum AFM parameters, energy and acting forces were established by a developed ANN model by Jain *et al.* [32, 33].

A stochastic model, which is related on surface that was finished by AFM, was developed by Williams and Rajurkar [18] the using Data Dependent Systems (DDS) methodology, they estimated the ratio of surface roughness R_z to R_a which is between 1.4 and 2.2 for the AFM process, by DDS methodology. They have recognised two types of wavelength profiles which were developed by AFM finished surface, a large wavelength is parallel to the flow direction of abrasive while the small wavelength is related with the cutting edges.

To determine the properties of the media flow during finishing and to verify experimentally mathematical simulation model was developed by Rajeshwar *et al*. [34] using viscoelastic Maxwell model which is a constitutive equations of taking the media properties as a non-Newtonian flow. They presented that a linear relationship between the material removal thickness and the shear stress acting on the surface.

Jain *et al*. [28] developed a finite element model to predict the stresses developed by AFM finished cylindrical passages. The media had linear viscous flow property and media properties were independent of temperature and were constant with regards to time and space. A theoretical model was presented based upon the abrading in AFM. The abrasive shapes were assumed as spherical, load acting on each abrasive particle was taken constant and has the same penetration depth.

Gorana *et al.* [35] presented a theoretical model for studying forces acting on a single abrasive grain in AFM, compared experimental data with those of theoretical model results during AFM process.

Petri *et al.* [31] proposed neural network models to estimate the surface roughness and dimensional change in AFM process, and reported three neural network models (material removal with a non-circular flow path and a circular flow path, finishing applications). These neural network models are then paired off a heuristic search algorithm to select sets of machine setup parameters for the AFM process.

A cascade correlation neural network model was applied by Lam and Smith [36, 37] and a neural network model by Sarah *et al.* [30] to automotive engine air manifold finished by AFM process. They predicted when the finishing process should be terminated to achieve the required airflow rate through manifold body.

A back propagation neural network model was proposed by Jain and Jain [32] to determine the optimum AFM process parameters for improving its performance unclear proper operating limitations.

Numerical methods and theoretical models were developed to predict the finishing behaviour of the abrasive media during AFM process. The surface roughness and material removal rate (MRR) were estimated by using the finite element method [28, 38]. Stochastic simulation was also used to define the media active grain density on the workpiece surface [39]. This method could be easily extended to simulate the surface generation in AFM. Furthermore, the material deformation induced by the abrasive was developed to predict the force models of AFM process [35].

A finite element model was developed by Jain and Jain [38] to analyse the flow of the viscoelastic abrasive media in the AFM. The finite element method was used to predict the MRR and R_a in AFM process. Experimental results and theoretical results from the finite element analyses were compared. They discussed effects of AFM parameters on performance parameters and concluded that with increasing in media velocity the normal stresses and media extrusion pressure increased linearly. The workpiece holder design is essential to achieve the accurate normal pressure, so that the preferred surface finish value in AFM can be attained. The higher reduction ratios cause higher increases in the extrusion pressure. With increasing in reduction ratio, the normal stresses on the workpiece surface increased. With increasing the abrasive media concentration and media extrusion pressure, the material removal (MR), the change in surface roughness (ΔR_a) increased.

Jain [23, 28] and Fang *et al*[40] also used finite element method for modelling the AFM process in order to evaluate the forces and stresses assuming that the sliding action of active abrasive particles were sliding and rolling while loaded. It was also presented that material removal (MR) efficiency is decreased by the rolling.

An analytical model was developed by Gorana *et al*.[41] to simulate and to estimate the surface roughness for various machining conditions in AFM. For modelling the interaction between the grains and the workpiece, a kinematic analysis was performed. For describing the grain-workpiece interaction AFM process parameters such as the abrasive concentration, abrasive mesh size, grain spacing, active grain density, forces on the particle, initial surface roughness (R_a), and initial topography of the workpiece were used. Experimental results were verified by the simulation results. They concluded that with increasing abrasive concentration and media extrusion pressure, active grain density increases during the AFM process.

Williams *et al.* [42] developed an acoustic emission technique for online monitoring of AFM performance parameters such as surface roughness and material removal. The effects of the AFM parameters were examined on MR, root mean squared of acoustic emission signal (AERMS), and surface roughness improvement. Only mesh size exhibited an insignificant effect on material removal. They used DDS technique to analyse the acoustic emission signal acquired during AFM process. They reported the fact that the higher frequency component is associated with the ploughing mechanism which would agree with the results obtained during grinding. They also found that aluminium workpiece gave stronger signals than steel workpiece because of higher material removal from aluminium workpiece in comparison with steel under identical finishing conditions. They found a strong correlation between the material removal rate and the acoustic signal in AFM.

A theoretical mathematical model were developed by Dabrowski *et al.* [43] for the media flow in AFM process, which includes the constitutive equations and the equations of momentum and continuity. Using the finite element method (FEM) they simulated a rigid flow through a slot in workpiece, and showed a linear relationship between velocity and pressure of the piston. As the piston velocity increases, material removal (MR) increases. The simulation results for material removal (MR) were good agreement with experimental ones. The pressure also dropped in the narrow channels through which the media flowed [44]. Hence, actual material removal (MR) was less than the theoretical model.

A deterministic and stochastic technique was used by Williams [5] to understand the complex and random nature of AFM process, and to investigate the metal removal mechanism which can be integrated with an on-line control strategy. To complete the study they took some specific interactions between parameters. From the experimental results, a high correlation was obtained between the acoustic emission level and the AFM process parameters.

A neural network-based process monitor and off-line controller system were developed by Smith and Slaughter [45] for AFM finishing of automotive engine intake manifolds. When the process achieved air flow specification so that machining could be terminated by the neural network model. This model uses proxy process parameters as inputs because of the inaccessibility of the product parameter of interest, air flow rate through the manifold during processing.

2.4 AFM Media Parameters

The rheological properties of the abrasive media and AFM parameters are two important factors affecting the efficiency of the AFM consequently, the AFM parameters directly affect the surface quality [12]. Moreover, the media extrusion pressure and abrasive media viscosity significantly affect the surface roughness and the material removal (MR) [6].

Some researchers [46, 47] studied the rheological properties of the abrasive media. The experiments indicated that the temperature change had a significant effect on the viscosity of the abrasive media. A small increase in the temperature causes a reduction in the abrasive media viscosity. The results also presented that the abrasive media viscosity decreased with the abrasive size but increased with the abrasive concentration [48].

Simulations using non-Newtonian fluid [34] showed that for forcing media through the hole of 29 mm in diameter there was a linear relationship between the applied pressure and the speed of flow [34].

Williams and Rajurkar [6] studied effects of the media viscosity and extrusion pressure on surface roughness and material removal (MR). The influence of the media viscosity is more important on material removal in comparison to those of the extrusion pressure. They reported that, in a few cycle, the major improvement occurred in the surface, and showed that media extrusion pressure and abrasive media viscosity dramatically affected both the material removal rate (MRR) and the surface roughness. The flow of the non-Newtonian fluid was simulated by Rajeshwar *et al.* [34] over the edge of the workpiece, and was concluded that there was a linear relationship between simulation and experimental results.

Dong *et al.* [49] derived an equation of motion and rheological theory of AFM in a slit-shape workpiece. They analysed the relations between the wall slip and grinding and developed the grinding model of AFM. The results showed that the wall slip was one of the essential parameter in AFM, and main factors affecting on the wall slip were viscosity coefficient, grinding coefficient of AFM, and the first normal stress difference.

Fletcher *et al.* [50] studied the relationship between the media rheological properties and the AFM process. The shear rate of the polymer increased while it was passing through the restriction (or reduced cross-sectional area). Capillary rheometer was used to find the relationship between the wall shear rate and the shear stress for abrasive media viscosity of polymeric abrasive media. They concluded that the coefficient of viscosity decreased but shear stress increased as shear rate increases. The variation of wall shear stress versus time are also studied. They also concluded that higher finishing action could be achieved as a result of longer machining time, due to higher wall shear stress generated.

Material removal mechanism was studied by Dabrowski *et al.* [51]. They concluded that the micro-chip formation affected by the abrasive particles of the media caused the material removal. The results showed that, if oil concentration in the abrasive media increased, then abrasive grids got loosely bounded with the base polymeric carrier. Low viscosity in media caused sliding action instead of indentation over the workpiece surface. [52]. Therefore, as increasing in oil content in media, decreased the percentage improvement in surface roughness. Jain *et al.* [38, 47] explained why material was removed by abrasive media and surface roughness was increased according to the changes in abrasive media viscosity, temperature, abrasive mesh size and concentration.

The AFM working efficiency was investigated by Fang *et al.* and Jain *et al.* [40, 47]. The effective parameters studied such as, abrasive media viscosity, temperature, abrasive density and shape, media flow speed, abrasive media pressure, etc. The temperature had the most critical effect on working efficiency of AFM. It was reported that as temperature increased, the media viscosity decreased. With increasing number of cycles, the temperature increased. Experiments showed that as increasing number of cycles, both surface roughness and material removal (MR) decrease. With increasing in media viscosity the material removal efficiency increased and improvement in surface roughness was higher than the low viscous media. The surface roughness improvement decreased with further increasing number of cycles because temperature rapidly increased with increase in number of cycles, the temperature rising directly decreased the media viscosity.

The fluid flow and thermal properties of polymeric carrier were studied by Fletcher *et al.* [50] for AFM process. It was presented that the rheology of the media donates considerably to the success of the AFM. The velocity of the media was dependent upon the main parameters of passage geometry, size and length, abrasive media pressure media viscosity.

Sankar *et al*. [53] reported that the change in cross-sectional area changed the abrasive media properties where the flow of abrasive media was under high pressure through a workpiece surface. This was due to the difference in shear rate to which it was exposed.

A viscometer set up based on the principle of viscoelasticity was developed by Agrawal *et al.* [54] to calculate the viscosity of the abrasive media by determining the bulk modulus and the creep compliance. For obtaining viscosity some measurements were made. Experiments were conducted at various temperatures and concentrations of the abrasive media. Results showed that the media viscosity increased as the abrasive concentration and temperature decreased. Different abrasive concentrations were compared with the values obtained from a capillary viscometer.

The various viscoelastic carriers were developed by Kar *et al.* [54]. The media was selected with respect to its rheological properties which were measured by rheometer. A two way AFM setup was used to evaluate the media performance. The investigation showed that a good surface improvement was achieved by only using styrene-butadiene rubber (SBR) media. Results also showed that the temperature, the shear rate, the strain, cyclic loading and time, etc. had effects on the rheological and mechanical properties of the newly developed abrasive media.

An effective and lower cost abrasive media was developed by Wang and Weng [48] to improve the surface roughness of the wire EDM surface. They concluded that silicone-rubber had good deformation and low flow effect; so that the flow can take place smoothly through the complex geometries. Also, the silicone-rubber was not stick on the workpiece surface after finishing. Silicone-rubber and abrasive particles were mixed homogeneously to form the abrasive media. The chain hole shape workpiece cut by wire EDM, was finished using this abrasive media. They reported that the surface roughness value R_a decreased from 1.80 to 0.280 μm after 5 cycles. An improvement of 84 % was achieved for surface roughness

The abrasive media is one of the important component of the AFM process [55]. Due to its complex mechanism, it is difficult to develop the finishing model of the abrasive media. Non-Newtonian flow assumption was made for CFD-ACE+ software to define the abrasive media movement. A non-Newtonian flow equation was generated by selecting the viscosity and shear rate of different media. The properties of the abrasive media were studied by applying the AFM process parameters, and a relationship between the simulations and the experiments was defined. The simulations showed that the high viscous abrasive media abrades the complex geometry rather than the low viscous abrasive media. And the high viscous abrasive media generated higher shear force than the low viscous abrasive media in the same surface.

A low viscous abrasive media was formulated from available materials, and a pneumatic air driven abrasive flow machining setup was designed and produced by Wan *et al.* [56]. They performed experiments on wire EDM cut aluminium workpiece to evaluate the finishing performance of the abrasive media in AFM process. The results showed the critical role played by the normal stress differences in determining whether or not material removal and hence polishing occur. Thus, the media must be adequately viscous to suspend the abrasives, all three viscometric measures must be considered in characterising the efficiency of the media used in the experiments.

2.5 AFM Workpiece Parameters

Jain and Adsul [12] reported that initial surface roughness and hardness of the workpiece affected material removal during AFM process, and material removal (MR) and ΔR_a were given for the case of softer workpiece material and harder material. ΔR_a and Material removal (MR) increased when abrasive concentration increased. They also concluded that among all the process parameters studied, the dominant parameters were the number of cycles, the abrasive mesh size and the abrasive concentration and it was also reported that with increasing abrasive mesh size, both ΔR_a and MR decreased. However, the study was carried out for brass and aluminum as hard and soft materials, respectively. Therefore, it was necessary to show the influence of the hardness of the steel on the AFM process.

Loveless *et al.* [11] reported the effects of AFM process on the various machining processes. The comparison of the turned and milled surfaces indicated that wire EDM'd surfaces were more suitable for AFM. The amounts of material removal from the wire EDM'd and milled surfaces were significantly different from that of turning and grinding, because these machining processes produced different micro surface contours.

Uhlmann *et al.* [57] investigated the principles AFM process on advanced ceramic materials in terms of a correlation among edge rounding, surface formation and flow processes. Furthermore, a process model was defined. The objective of this study was to work both edge rounding and surface quality on any user defined geometry. The results showed that typical smooth surface textures occurred, edges and micro cracks were removed. The advanced ceramics had ductile material removal mechanism with finished by 44.5 µm abrasive grid and had brittle material removal mechanism with finished by 185 µm abrasive grid. Increasing temperature caused decrease in the viscosity of abrasive media, hence the material removal rate decreased. As the media pressure increased and the flow cross section decreased, the material removal rate and the media velocity increased.

The material removal (MR) mechanism was studied by Sehijpal Singh *et al.* [58] in AFM process. Brass and pure aluminium were used as workpiece materials under the same AFM conditions. The scanning electron microscopy (SEM) photographs showed that different abrasion paths were produced on the different workpieces. A material removal (MR) mechanism was suggested by examining the nature of interaction between the target workpiece surface and the abrasive media.

2.6 Other Processes Developed from AFM

Fundamental AFM process has some limitations. Industrial and academic research has led to the creation of new abrasive flow machining processes, researchers have tried to overcome these limitations by using hybrid approach [59, 60] and have reported improvement in the efficiency of new AFM processes.

Applied centrifugal forces to the abrasive media during the AFM process is called centrifugal force assisted abrasive flow machining (CFAFM) process. Furthermore, a new finishing process by applying a magnetic field around the workpiece that is called magneto rheological abrasive flow finishing (MRAFF) [20, 44]. Applying the magnetic field to the AFM process, causes radial and axial forces [20, 61] the material removal (MR) increases [22, 35].

For cylindrical workpieces, researchers have developed some other processes such as rotational abrasive flow finishing (R-AFF) process where abrasive media was rotated by using a rod, improves finishing capacity. Increasing the number of active grains produces better circularity of a finished cylindrical parts [60, 62]. Some researchers planted spiral fluted screw in the flow path of abrasive media to improve surface quality [63]. Mathematical models were developed for computer simulation of AFF process while finishing cylindrical workpiece [34]. A new set up was developed by Ravi Sankar *et al.* [64] to improve the performance parameters such as surface finish and material removal rate MRR by use of a rotating workpiece in the abrasive media.

Rotational abrasive flow finishing (R-AFF) process was studied to examine the effects of the process parameters on performance parameters [64]. Al alloy and Al alloy/SiC metal matrix composites (MMCs) were used as workpiece material. In this case, R-AFF could produce 44% better ΔR_a and 81.8 % more MR compared to the conventional AFF process. Accordingly, R-AFF generated micro cross hatch patterns on the finished surface that can also improve lubricant holding capabilities.

A rotating centrifugal force generating (CFG) AFM process were identified by Walia *et al*. [65-68] to improve surface roughness. Centrifugal force acts to the abrasive grids normal to the axis of workpiece by aid of a rotating rod to examine the effect of the process parameters on the performance. The results showed that the same surface quality could be achieved with less number of cycles. The significant process parameters were CFG rod speed, abrasive mesh size and extrusion pressure.

A drill bit was used for improving the performance of AFM by Ravi Sankar *et al*. [69]. This is called drill bit-guided abrasive flow finishing (DBG-AFF). The abrasive flow path in DBG-AFF process was longer than the AFM abrasive flow path. It caused more surface finish improvement in DBG-AFF than conventional AFM. As the drill bit diameter decreases, the material removal (MR) decreases.

Liao *et al*. [70] pointed out that conventional AFM methods had difficulty achieving uniform roughness of an axial distribution in circular hole polishing due to limited unitary axial motion of abrasive media. Therefore, they developed mechanism designs for different passageways to obtain multiple flowing paths of abrasive media, whose flowing behaviour enhanced polishing effectiveness by increasing the abrasive surface area. The roughness deviation of six helices passageway of approximately 0.1 μm R_a was significantly better than those on a circular passageway of around 0.17 μm R_a.

Centrifugal force assisted abrasive flow machining (CFAAFM) was studied by Reddy *et al*. [71] to examine the effects of the process parameters on performance parameters of CFAAFM process. Al alloys (2014) were used as workpiece material, and a higher improved performance of CFAAFM was achieved over traditional AFM in terms of improved surface finish and material removal

Das *et al.*[72] explored magneto rheological abrasive flow finishing (MRAFF) process that was a combination of AFM and magneto rheological finishing (MRF), developed for precision parts, complex geometries and for a wide range of industrial applications. They studied the theoretical investigations of MRAFF mechanism and studied the effects of AFM process parameters. A finite element method was implemented to evaluate the stresses developed during the process. The effect of magnetic field on the rheological properties of the media was studied by using a capillary viscometer which was fabricated for this study. Acting forces on the abrasive particle were calculated from the applied magnetic field. The microstructures of abrasives were examined. Surface roughness and material removal prediction model were presented and theoretical results were verified with the experimental data available in the literature.

A comparative experimental study between the traditional AFM and MAAFM was presented by Sehijpal Singh *et al*. [61] to investigate the material removal (MR) mechanism and the wear behaviour of some materials. The magnetic field had a strong effect on the MR in MAAFM, and the underlying wear patterns on the surfaces were observed by using SEM.

MAFM process was studied by Singh and Shan [20] to investigate the effects of the process parameters on performance of AFM. MAFM process improved performance parameters than traditional AFM and more material removal MR and Δ R_a are examined with the less number of cycles.

Magneto-rheological abrasive flow finishing (MRAFF) process was developed by Das *et al*. [73] for finishing of parts even with complicated geometry for a wide range of industrial applications. A mixture of magnetic and abrasive particles in MRPF was suggested, and normal force on the abrasive particles was calculated from the applied magnetic field. A model for the prediction of material removal MR and surface roughness R_a were presented. Theoretical results were in a good agreement with the experimental data available in the literature.

Magnetorheological abrasive flow finishing (MRAFF) process was studied by Jha and Jain [74, 75] for finishing complex internal geometries. Effects of the process parameters on performance parameters were studied. Stainless steel and silicon nitride were used as workpiece material whereas Silicon carbide, Boron carbide and Diamond were used as abrasive. The best surface finish was achieved on the stainless steel workpieces.

Electrochemical aided abrasive flow machining (ECAFM) was studied by Dabrowski *et al.* [43, 51]. Polymeric electrolytes were used. The experimental evaluation of several solid electrolytes with various bonds was carried out. The abrasive properties of the electrolytes were enhanced by adding the Al_2O_3 and SiC grains and its consistence was adjusted by the SiO_2 addition.

CHAPTER 3

ABRASIVE FLOW MACHINING AND CHARECTERISTICS EDMed SURFACES

3.1 Introduction

This chapter presents the explanations of the abrasive flow machining process and its details such as machine types, main components, process parameters and working procedures. EDM surface characteristics are also explained in this Chapter.

3.2 Abrasive Flow Machining

Owing to the fact that the traditional finishing operations must provide high skilled labour, the cost of the finishing process is estimated nearly 10-15% of the total manufacturing cost. This demand changes with respect to the workpiece complexity in the profiles and geometric shapes and dimensional accuracy. The geometric and dimensional accuracy and surface quality are taken care of by finishing processes [22]. Recent advances in technology have led to the advent of more innovative automated finishing processes. Abrasive flow machining (AFM) is the one of these non-traditional finishing process.

To meet these demands, specific forms of surface finishing processes have been developed. These new, or non-traditional, surface finishing processes were designed to solve problems in the aerospace industry but are now being used in a variety of applications throughout many industries [4]. One such non-traditional process, Abrasive Flow Machining (AFM), was developed for the deburring of aircraft valve bodies and spools in the 1960's [4, 76]. Abrasive flow machining AFM is a non-traditional polishing process in which a polymer based media consist of abrasive particles in the media cylinder is extruded under pressure back and forth through or around the workpiece surfaces, with the aid of hydraulic actuator. Nowadays, the usage areas of AFM process spread out to different industries.

AFM has been used to polish, clean, deburr and produce a radius edge on workpiece where traditional finishing processes are not possible.

Since its invention, AFM has become an important part of finishing processes with many machines currently being used throughout the different industries such as aerospace, automotive, and die-making [12].
Abrasive flow machining AFM process can achieve inaccessible surfaces of complex workpiece, processing multiple small holes, slots or edges in one operation and has the ability to improve the thermal and mechanical fatigue strengths of a workpiece by removing stress raisers on sharp corners [15].

Thousands of components can be finished by using Abrasive flow machining AFM processes per day. AFM process significantly reduces the labour costs in traditional finishing processes. The well-known AFM application areas are as follow:

- Edge finishing of holes and features to improve fatigue strength of aircraft blades, disks, hubs and shafts,
- Finishing various component surfaces after casting, milling, and Electro Discharge Machining (EDM) or Electro Chemical Machining (ECM) operations [11],
- Finishing automotive engine manifold runners to improve power output [36],
- Removal of recast (white) layer that is produced in EDM process. To improve the surface quality of the workpiece [3],
- Finishing and deburring in diesel engine injection nozzles to improve the engine performance [77],
- Die and mould industry to make the surfaces clean and polish [78].

3.3 Machine

The main function of the AF machine is to stock the abrasive media and control the main AFM process parameters such as extrusion pressure, media flow velocity, media volume, and number of cycles.

Extrude Hone is the main commercial AF machine producer. Commercial AF machines are available in a variety of different sizes with a range of skills with extrusion pressures that range from 700 to 22000 kPa and flow rates above 380 litre per minute [79]. Also the same company is the main supplier of abrasive media. Some media parameters are affected by the machine configurations i.e.; the flow rate of the media depends on the media pressure, the media viscosity, and the workpiece and tooling configuration. AFM machines are classified into four categories: one-way AFM, two-way AFM, orbital AFM and magnetically assisted AFM. AF machines consist of three main units, such as hydraulic power unit, electronic control unit and main frame. A brief discussion of them is given in the following section.

3.3.1 One-way AF Machine

In one-way AF machine, the process is achieved by use of the hydraulic piston. As shown in Figure 3.1, in one-way process, the abrasive media is housed by the media cylinder and it is extruded through the restricted workpiece surface by help of the hydraulic piston’s ram. The abrasive media is forced to flow through the workpiece internal or external surfaces by the use of the complicated designed workpiece holder equipment. To complete the cycle for one-way AFM process a media collector is used, because the one end of the cylinder is open. The hydraulic piston is moved backward to the initial piston position and the entrance of the media cylinder is opened. Then the used media is filled in to the media cylinder to start the next operating cycle of AFM process [80].

3.3.2 Two-way AF Machine

Commercial AF machines are commonly available as two-way AF machines. They have two vertically opposed chambers which contain the abrasive media cylinders, the hydraulic clamping pistons, the main actuating pistons, the support and the control system.

The lower chamber is held stationary in the machine base although the other, (in the head structure), moves vertically on guide of clamping pistons. A schematic view of two-way AFM process is given in Figure 3.2.

Each chamber contains a hydraulic piston and a ram on the tip of the piston to move the abrasive media from one media cylinder to the other. The diameter and length of the media cylinder determine the machine's volumetric capacity. Whole machine has adjustable controls. To provide desired parameters, automated control systems are added to the machines to monitor and control the AFM process parameters[80].

These adjustable parameters are:

- The media extrusion pressure,
- The media flow rate,
- Number of cycles,
- An optional media displacement control.

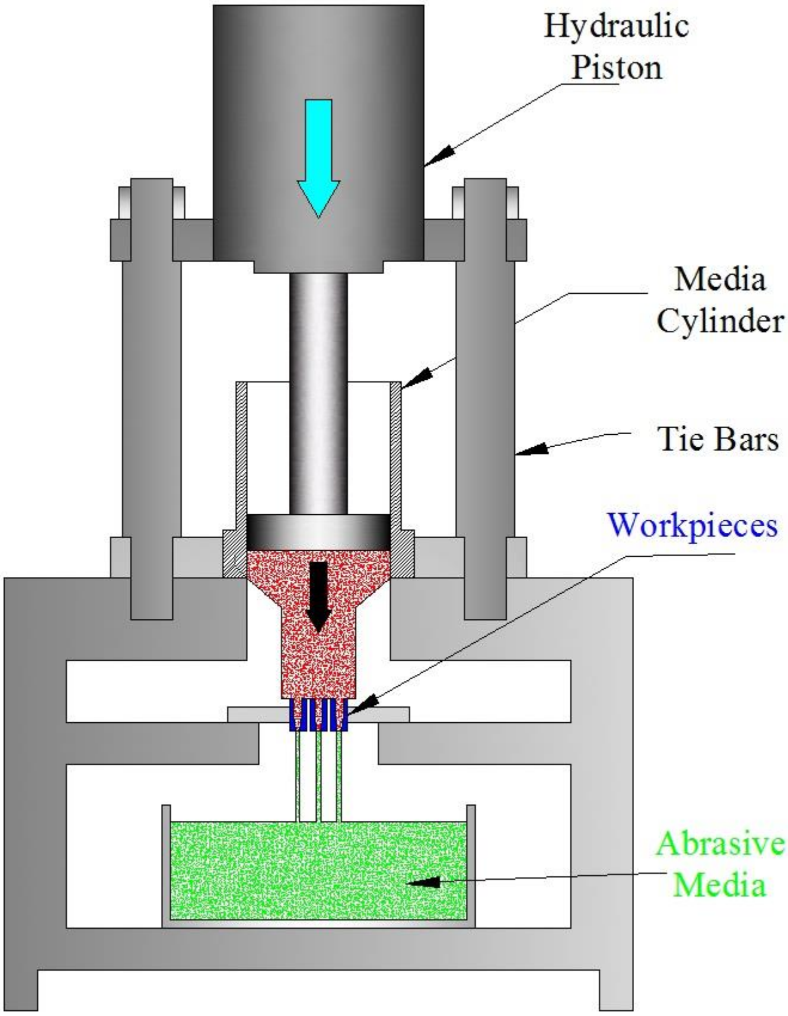


Figure 3.1 One-way AF machine

3.3.3 Orbital AF Machine

Industrial and academic research has led to the creation of two new abrasive flow machining processes, Orbital AFM (OAFM) and Magnetically Assisted AFM (MAAFM).

Extrude Hone pioneered a development to the conventional AFM process, namely Orbital AFM (OAFM). The same principle of machining for conventional AFM is used in OAFM, but with a few changes. The workpiece is held within a fixture and fine abrasive media flows through or around it, shown in Figure 3.3. Whilst the media flows, the workpiece vibrates with small amplitude oscillations (typically 0.5 to 5 mm) in two or three dimensions.

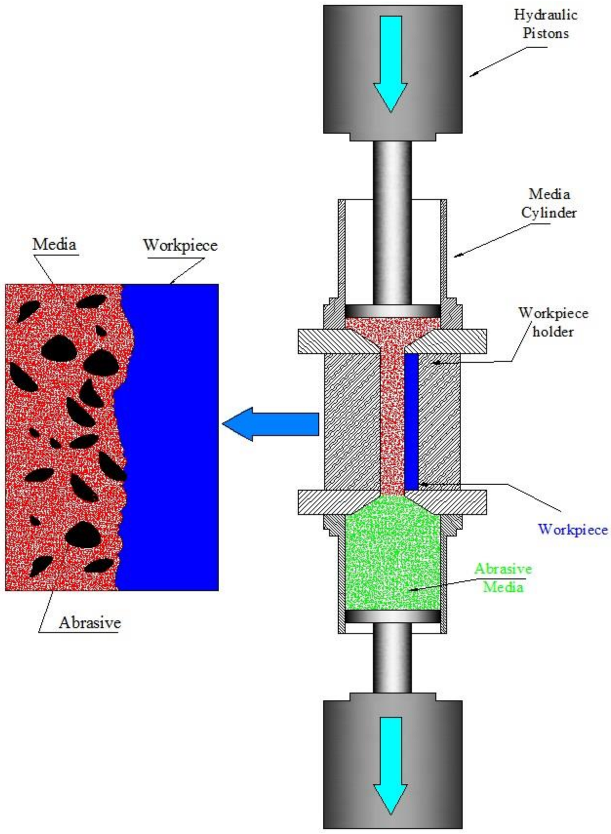


Figure 3.2 Principle of material removal mechanism in two-way AFM process

3.3.4 Magnetically Assisted AFM (MAAFM)

Magnetically Assisted Abrasive Flow Machining (MAAFM) is a concept presented by Singh *et al.* [20]. Singh designed and manufactured an AF machine with an electromagnet positioned around a cylindrical workpiece (see Figure 3.4). The principles of the operation being similar to the conventional AF machine discussed earlier in this chapter.

The abrasive media is required to be magnetic, thus, a number of magnetic additives are mixed into a conventional media. As the media is extruded, the electromagnet attracts the abrasive particles towards the internal surface of the workpiece. The principle is that more of the abrasive particles within the media will come into contact with the workpiece and thus increase material removal rates and improve surface finish [20, 61].

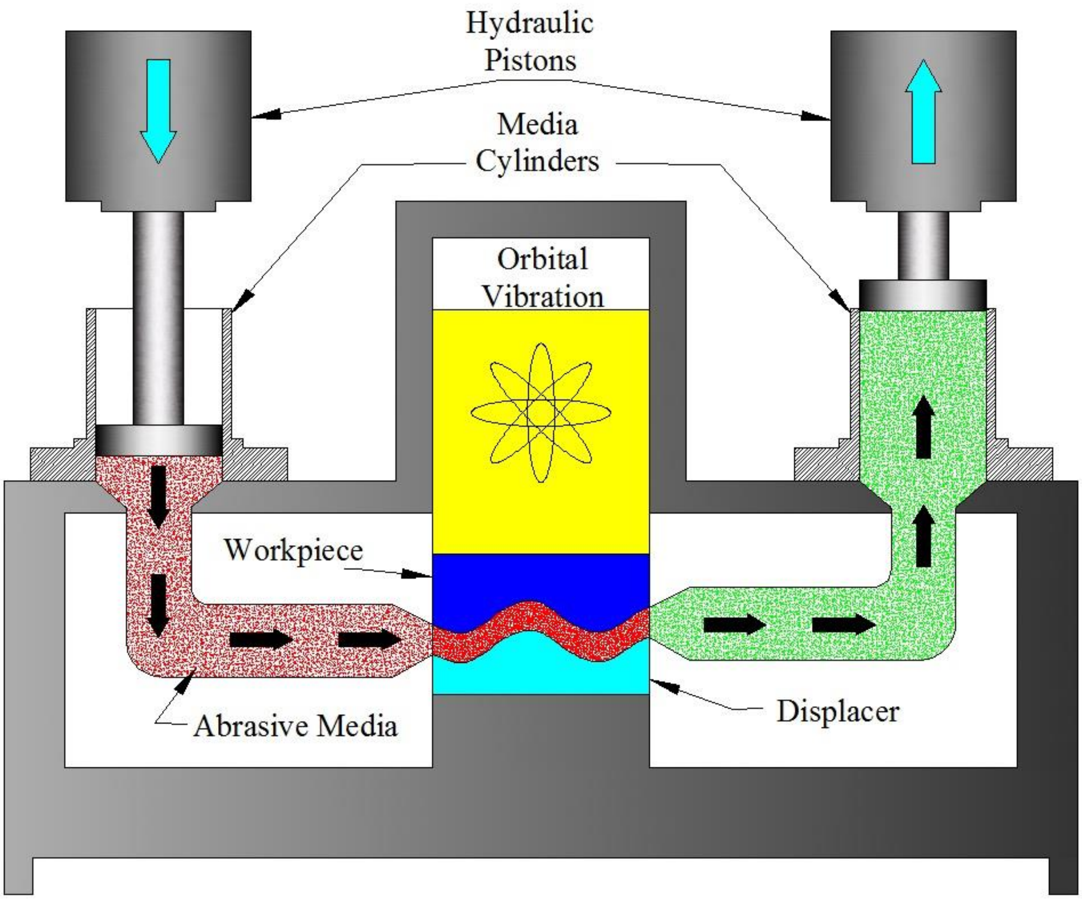


Figure 3.3 Orbital AFM

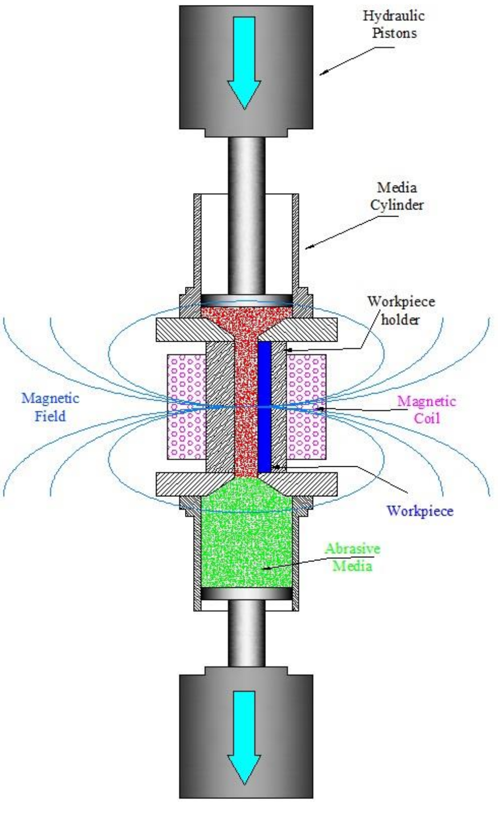


Figure 3.4 Magnetically Assisted AFM (MAAFM)

3.4 Workpiece Holder

The workpiece holder performs many functions in the AFM process since it not only influences the positions where abrasion occurs but also enables selective abrasion surface to be attained, protects critical edges and surfaces, and assists in loading and unloading of workpiece[4].

The workpiece holder geometry is dependent upon the component to be polished and its requirements. Because of its low cost, steel is generally used for the workpiece holder but if weight is a problem then materials both light weight [aluminium and plastics (e.g. structural nylon)] can be used. To protect the workpiece holder surface from abrasion the polyurethane elastomer coatings are used. Also these coatings may also be used to protect certain sections of the work piece that do not require finishing.

Many AFM applications require only simple workpiece holder. Dies, for example, typically need no special holders, because the die passage itself provides the restriction for the flow path. For external edges or surfaces, workpiece holder is used to restrict the flow between the outside of the part and the inside of the workpiece holder shown in Figure 3.5.

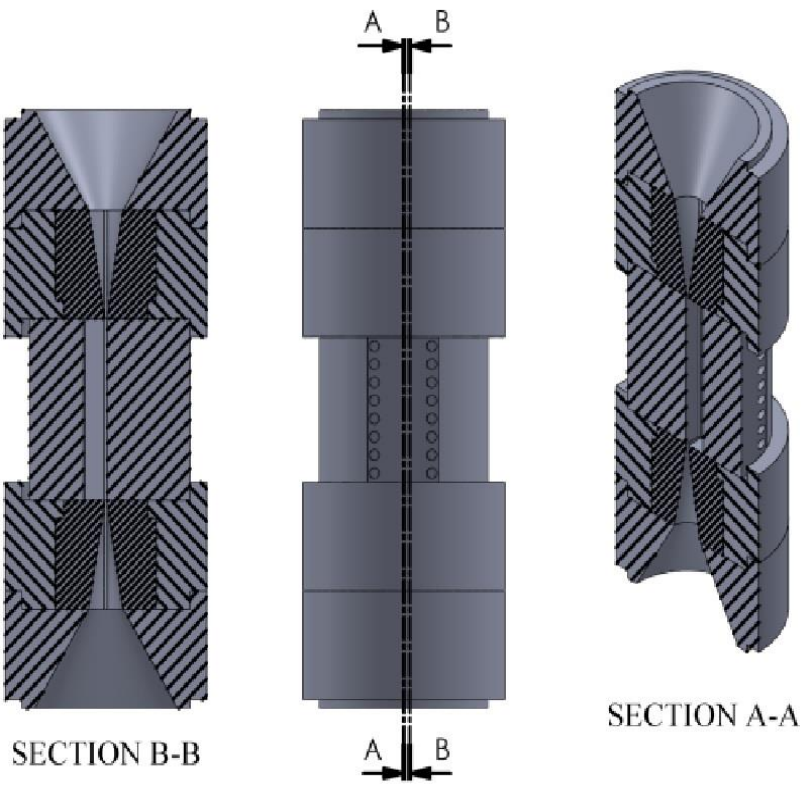


Figure 3.5 Workpiece holder

3.5 Abrasive Media

The abrasive media is one of the main elements in the AFM process. The abrasive particles are held in the polymeric matrix such that a uniform distribution is obtained throughout the abrasive media. Polymeric carrier adapts exactly to the workpiece geometry insuring 100 % contact on all workpiece surfaces. Polymeric carrier also has good cohesion and little tendency to adhesion.

In order to reach the desired amount of surface improvement and material removal, different size, type, and percentage of the abrasive particles coupled with the viscosity of the polymer are used in AFM process. Abrasives are chosen as silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C), and diamond for abrasive flow machining AFM process. Silicon carbide (SiC) is the most widely used abrasive in the AFM process since it lasts longer and is cheaper than the alternatives. Aluminium oxide (Al_2O_3) is also used in a variety of applications, since it performs well, but is used less frequently than silicon carbide because of the cost. Due to the high cost of both diamond and boron carbide (B_4C) they are only used to polish very hard materials such as tungsten carbide. To reduce the friction during extrusion of the abrasive media, some lubricants are added to the base polymer [76]. A view of abrasive media is shown in Figure 3.6.

Figure 3.6 A view of abrasive media

3.6 AFM Procedure

The media is loaded into the lower media chamber followed by the clamping of the component and tooling in position between the two media chambers. The media is then forced from one chamber into the other under hydraulic pressure. The media viscosity temporarily rises during extrusion through any regions of restricted flow, such as burrs or restrictions induced by the tooling, causing the abrasive grit to become held rigidly by the polymer. The media then acts as a multipoint-cutting tool transmitting the force applied by the machine to the component edges and/or surfaces which results in stock removal and surface improvement. ["The amount of force transmitted to the abrasive grit in contact with the component depends upon the media consistency and the pressure differential from one side of the grit particle to the other" [4]]. The higher the media viscosity the greater the percentage of force transferred to the abrasive grit. However, not all the applied pressure is consumed in machining; a fraction of it is expended in internal shearing of the media as well as in deformation of the media to the form of the restricted flow path. After passing through the restricted passage the media viscosity returns to its original value. One extrusion cycle is completed when the media is extruded from the lower media chamber to the upper media chamber and back again. Analogously, the process can be thought of as a flowable file, with capabilities ranging from a light buff to coarse stock removal. Once the component has been machined any media remaining must be removed. This is achieved by either air or vacuum which removes the vast majority but in the case of very complex components the media is sacrificed by removal in a solvent wash or bath. The removal of media need not be immediate since it does not dry-out.

3.7 AFM Process Parameters

It is proposed from the literature review, The AFM process parameters are dependent upon:

- The media extrusion pressure,
- The abrasive grit type, size, and percentage,
- The media viscosity,
- The geometry of the tooling and component,
- The number of cycles,

- The workpiece material.

The AFM process parameters can be classified on the basis of three major groups of the process, as stated follow,

- AFM Machine Parameters: number of cycles, extrusion pressure, media flow rate, media flow volume,
- Abrasive Media Parameters: abrasive type, abrasive mesh size, abrasive concentration, additives, temperature and viscosity of the media,
- Workpiece Parameters: workpiece material, passage geometry, reduction ratio, initial surface quality, pre-machining surface workpiece hardness.

A brief description of each of these AFM process parameters are presented in the following section.

3.7.1 Machine Parameters

3.7.1.1 Number of Cycles

An operating cycle is a term used in AFM to describe the reciprocating action of the AFM machine. A cycle in one-way AFM is composed of the abrasive media filling stage of the media cylinder and complete forward stroke, then hydraulic piston is moved backward to the initial position. This combination of forward and reverse strokes completes one cycle of the one-way AFM process. One cycle on common two-way AF machine involves the abrasive media being extruded through the workpiece from the bottom media cylinder to the top media cylinder then from the top to the bottom media cylinder, thus completing a cycle.

3.7.1.2 Extrusion Pressure

Extrusion pressure is the pressure developed inside the media cylinder with which the media extrudes through or past the workpiece surface thereby causing finishing by the abrasive action of the abrasive media which acts as a flowing tool in this process.

The pressure of the media is controlled through the two opposing media cylinders of the AF machine. AF machines are capable of extrusion pressures ranging from 7 to 220 bar [15, 16].

3.7.1.3 Media Flow Rate

The displacement of the two extruding media cylinders determines the media flow volume and the number of cycles within a sequence [79]. The velocity that the media cylinders extrude the media determines the flow velocity. Media flow volume divided by the processing time gives the overall process flow rate. Media flow rates are usually measured in cm^3/s or litre/s, whilst flow velocities are usually measured in mm/min. The flow velocity and flow rates are dependent on the speed at which the AFM machines pistons move, which can be varied and set by the machines controller.

3.7.2 Media Parameters

3.7.2.1 Abrasive Types

Most widely used abrasives are silicon carbide SiC, aluminium oxide Al_2O_3, boron carbide B_4C and diamond in abrasive flow machining AFM process [76].

The choice of abrasive particles is dependent on the workpiece material with respect to the density and physical properties and also the requirements of the final surface roughness.

Silicon Carbide (SiC) is most widely used abrasives because it is very hard, durable and a consistent performer over a wide spectrum of applications.

Aluminium Oxide (Al_2O_3) is the preferred choice when a metallurgical inert abrasive is required, such as the finishing of high-nickel, super-alloy aircraft engine blades and vanes, semiconductor valves and tubing, and numerous medial implant applications.

Boron Carbide (B_4C) is the second hardest known material next to diamond. It produces a faster material removal rate than silicon carbide under ideal cutting conditions. Boron carbide is also lighter than silicon carbide and as a result, up to 25% more media by volume will be found in unit weight. Boron carbide is applied on low-machinability materials, such as hardened tool steel, cobalt steels, nickel-based super-alloys, titanium, and tungsten carbide applications.

Diamond Powders are used for special applications, such as workpieces that require a high-quality surface finish or are made from extremely hard materials like tungsten carbide. Typical examples are extrusion, drawing and heading dies or where a high-gloss finish is required.

3.7.2.2 Abrasive Mesh Size

Abrasive mesh size represents the grain size of the abrasive particle. The size of grains range from 5μm to 1.5mm [10, 16]. It is common practice for the media manufacturer not to limit the process to one-grain size in each media base. Two or three different gain sizes are often used within the same media base make-up, dependent on the required results [12, 17].

3.7.2.3 Abrasive Concentration

Abrasive concentration is defined as the ratio of weight of the abrasive particles to the total weight of abrasive media multiplied by 100.

3.7.2.4 Viscosity of the Media

Viscosity is a fundamental property of all liquids. When a liquid flows, it has an internal resistance to flow. Viscosity is a measure of this resistance to flow or shear. Viscosity is a function of temperature and pressure. Viscosity is mainly dependent upon the type of polymer used for media formulation and the percentage oil concentration in the media.

3.7.3 Workpiece Parameters

3.7.3.1 Material Type

Although workpiece material is not an operating parameter that can be altered by the AFM process or equipment, it is none the less a significant factor in affecting the selection of the operating parameters. Research on the AFM of different workpiece materials clearly shows that the workpiece material introduces some variability and has an influence on the output results.

3.7.3.2 Workpiece Passage Geometry

Finishing processes have some limitations such as complex workpiece geometry. For example lapping and grinding processes can be applied to flat or circular surfaces. In die and mould manufacturing industry, the complex shaped extrusion dies are manufactured from the hardened bulk tool steel by using WEDM cutting process. These complex workpiece surfaces must be cleaned and polished before operations. So these workpiece surfaces can be effectively finished by AFM process.

3.7.3.3 Behaviour of Initial Surface

Each manufacturing process produces surface finishes in a certain range, some of which may overlap although each possesses a unique surface pattern; for example turning and shaping leave parallel lines, grinding produces directional lines varying in length, milling produces concentric lines and honing and EDM produce random lines. The schematic view of main machining lays is given in Figure 3.7.

3.7.3.4 Material Hardness

In die and mould manufacturing industry, the dies and moulds are manufactured from the hardened bulk tool steel by using WEDM cutting process. And these parts must be cleaned and polished before operations. So the material hardness is an essential workpiece parameters for AFM process.

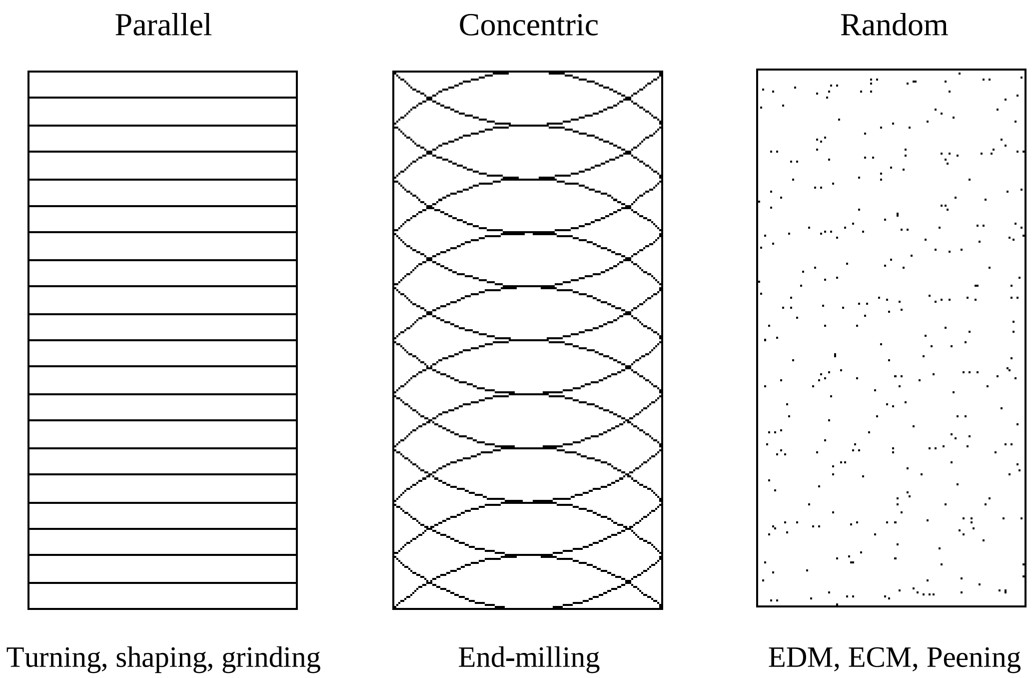


Figure 3.7 Machining lays

3.8 Output Performance Parameters

Material Removal (MR) and surface roughness (R_a) value can be taken as the output response indicating the performance measures of AFM process. Also SEM images and microscopic views are used for examining the surfaces.

3.8.1 Surface Integrity

Surface integrity is an important factor because the nature of component surface determines how effectively the component performs during its operation. This property involves both surface topography and surface metallurgy. The relevant parameters encompass surface finish, chemical change, thermal damage, and residual stresses, of which the most important factor is the surface finish. Surface finish is affected by the microstructure of the component material, the action and instability of the machining action, and deformations due to stress patterns in the component. The standard notation of surface finish is surface roughness (R_a) and is a quantitative assessment of the vertical and horizontal elements of a machined surface. The magnitude of this parameter is attained from the mean deviation of the peaks from the centreline of a corresponding surface profile.

3.8.2 Material Removal MR

Material removal (MR): signifies the amount of material that has been removed from the workpiece surface in finishing operation by AFM. It is estimated as the difference between the initial and the final weights of the workpiece.

3.9 Basis of EDM

3.9.1 Types of EDM

There are three main types of EDM; ram EDM, fast-hole EDM and wire EDM. All EDM machines use sparks to remove electrically conductive material [81]. However they use different electrode types, dielectric fluids. The operation technology and application field of them are different as well [82].
Ram type EDM (Figure 3.8) machines are used to produce three dimensional shapes as mould cavities [83]. The electrode and workpiece are submerged in a dielectric fluid, which is generally hydrocarbon oil. In order to machine desired shape, a formed

electrode is used. End of the operation, opposite shape of the electrode produced in the workpiece. In ram EDM sparking occurs between the end surface and the corners of the electrode and workpiece.

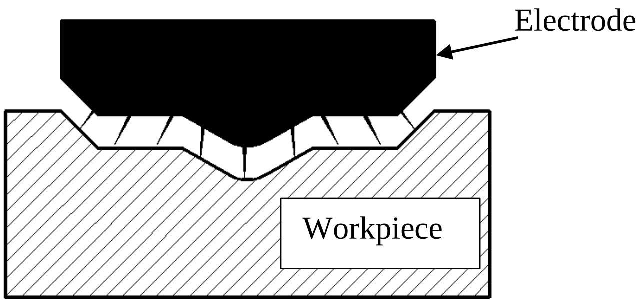


Figure 3.8 Schematic view of ram EDM

Small-hole EDM drilling machines, as shown in Figure 3.9, use the similar principles as ram EDM [81]. A constantly rotated hollow electrode and high pressurized pumping of dielectric fluid (deionized water) through the inner surface of electrode tube are the two separate features. The process is used to produce fuel injectors, venting holes of injection moulds, coolant holes of injection cutting tools, hardened punch ejector holes, wire-EDM starter holes, holes in turbine blades and other similar operations.

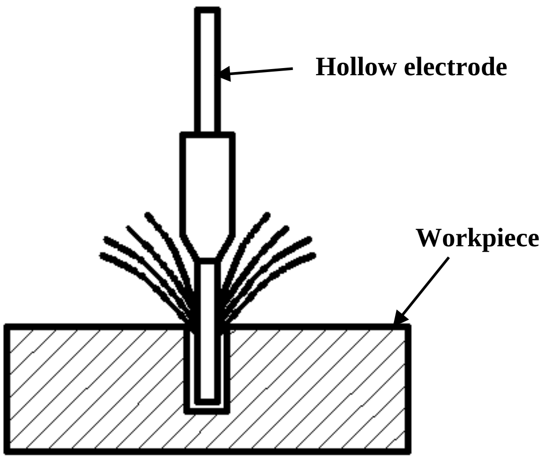


Figure 3.9 Schematic view of small-hole drilling EDM

Wire EDM is a special form of EDM which uses a continuously moving conductive wire electrode (Figure 3.10). Sparking takes place from the electrode wire-side surface to the workpiece. As the wire feeds from spool to spool, material removal occurs as a result of spark erosion on conductive work-piece along a computer-controlled (CNC) path by the relative motion of the machine's axis [82]. The wire is usually made of brass or copper, and is between 0.1 and 0.3 mm diameter. The dielectric fluid being used in wire EDM is a deionized water that are only sprayed into the sparking area. Extrusion dies and blanking punches are very often machined by wire cutting, since cutting always passes through the workpiece.

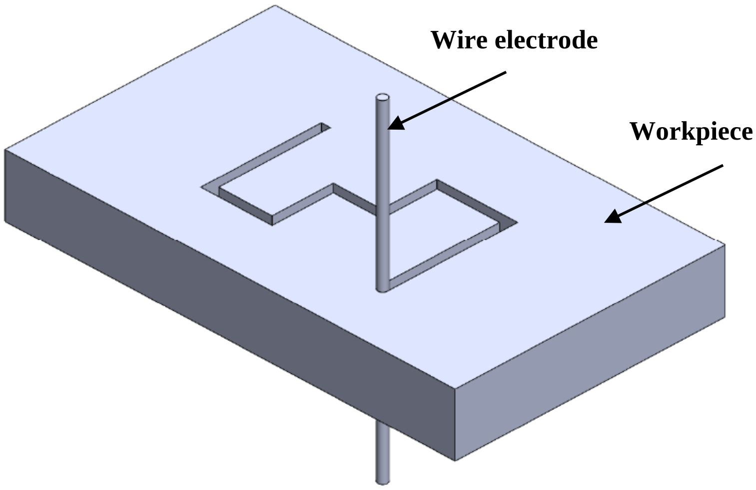


Figure 3.10 Schematic view of Wire EDM

3.9.2 EDM Surface Layers

The EDM process changes the surface and subsurface of the workpiece. Three layers are created on top of the unaffected workpiece metal (see Figure 3.11**)**. The surface can be analysed in three layers which is created by EDM. The spattered layer consist of molten metal and small amounts of electrode. This spattered material is easily removed.

During EDM process, rapid heating and cooling occur and they cause heat affected layer on the machined surface. This layer is generally formed by the sticking of the non-removed debris and also the depth of material affected from high temperature. The top of the layer consists of re-solidified layer and has re-cast structure. The recast layer seems white colour on microscope and thus it is commonly referred to as the white layer. The white layer is very hard and brittle and has micro cracks. The effects of white layer can cause premature failure of the part in some applications.

Under the recast layer a heat affected zone (HAZ) is present. This zone comprises the workpiece material that has undergone a thermal influence, but has not been molten. The HAZ usually consists of several layers, although it is not always easy to distinguish them. In the case of steel, usually a hardened (martensitic) and an annealed layer are present.

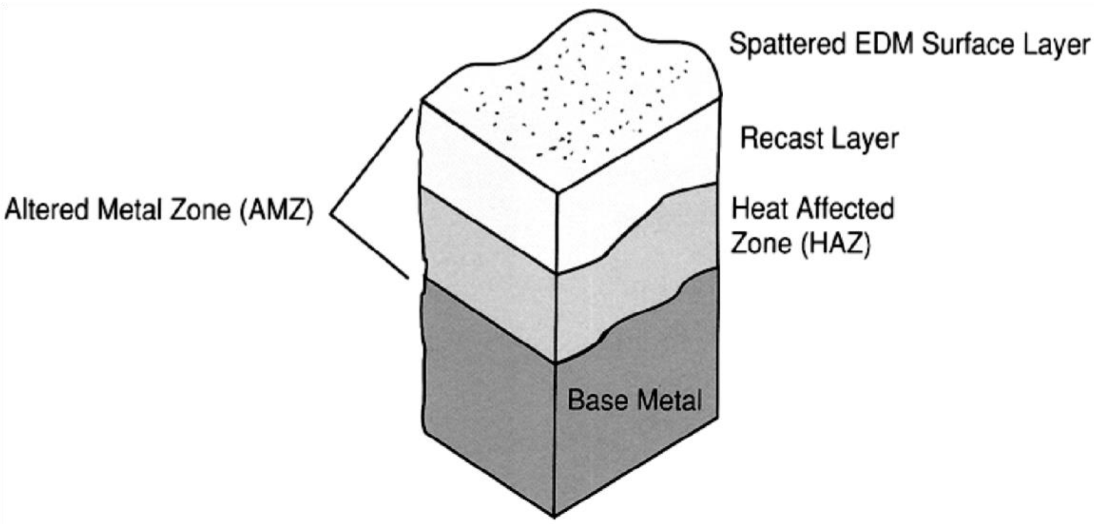


Figure 3.11 Surface layers after electrical discharge

3.9.3 Surface Integrity in EDM

Each successive pulse discharge in EDM produces a distinct crater on the surface of work piece and the tool electrode. The resulting surface consists of a series of randomly distributed overlapping craters with depth to diameter ratio varying from 5 to 50 μm. The quality of surface largely depends on the pulse energy and pulse duration. For small energy pulses surface finish comparable to that obtained in turning, planning or milling operations may be obtained. An interesting feature of EDM surface is that unlike conventionally machined surfaces, it has no definite direction of layer. This gives the surface a 'Matte' appearance, and better functional properties due to retention of surface oil film.

3.9.3.1 Surface Deformation

Immediately at the end of the discharge in EDM, the molten metal left over the crater is still at a sufficiently high temperature. This is cooled rapidly by the dielectric leading to solidification of the molten layer onto the substrate. High stresses produced due to contraction on cooling, and shock waves produced due to electric discharge can cause severe slip, twining, and cleavage in the affected layer depending upon the machining conditions employed. These defects accumulate at the grain boundaries and can lead to surface cracking. Even in ductile materials practically all spark-machined surfaces show some cracking and presence of high residual stresses.

3.9.3.2 Effect of EDM on Mechanical Properties of Workpiece

The presence of high surface residual stresses and micro cracks in components produced by EDM have a significant effect on the properties of the work material such as, fatigue life, and stress corrosion behaviour. Several investigators have reported a significant decrease in fatigue strength of the spark machined components. Rhoades [84] has quoted a 10-30% reduction in fatigue strength of steel parts when machined by EDM, whereas a 60% decrease in endurance limit. He further claimed that even finish machining by EDM can also prove to be detrimental to fatigue strength. Some improvement in fatigue life of the machined specimen is possible by imparting suitable heat treatment to the components machined by this process. However, if surface cracks are present, the damage is of permanent nature and the affected zone must be removed by lapping, polishing or by some other suitable means [85].

CHAPTER 4

DESIGN AND CONSTRUCTION OF AFM MACHINES

4.1 Introduction

Two types of AF machines (one way and two way) were designed and constructed to carry out the experimental studies. 3D SolidWorks design software was used for this purpose. The types and specifications of the machines were defined according to the literature and preliminary studies. In early stages of our AFM study, a conventional lathe was used. The piston movements were realized by help of the carriage.

Hydraulically actuated and electronically controlled AF machines were designed according to the preliminary AFM studies. The machines are composed of six main units namely:

- Main body (structure, frame),
- Hydraulic power unit,
- Electronic control unit,
- Cooling-heating unit,
- Media cylinders,
- Workpiece holder.

In the following sections of this chapter, the machines and their component are explained.

4.2 Design of AF Machines

4.2.1 One-way AF Machine

An one-way AFM, as shown in Figure 4.1, was designed and constructed to perform the experiments which can be applied to tapered holes, nozzles and similar geometries permit one-way flow.

The machine is composed of a main frame, a hydraulic unit, an electronic control unit, a workpiece holder and a media cylinder. The hydraulic piston and the media cylinder are assembled to the main frame by using bolt-nut joint. The conical nozzle is screwed to the lower end of the media cylinder to regulate the media flow. The workpiece holder is matched to the conical nozzle by the help of the hydraulic jack.

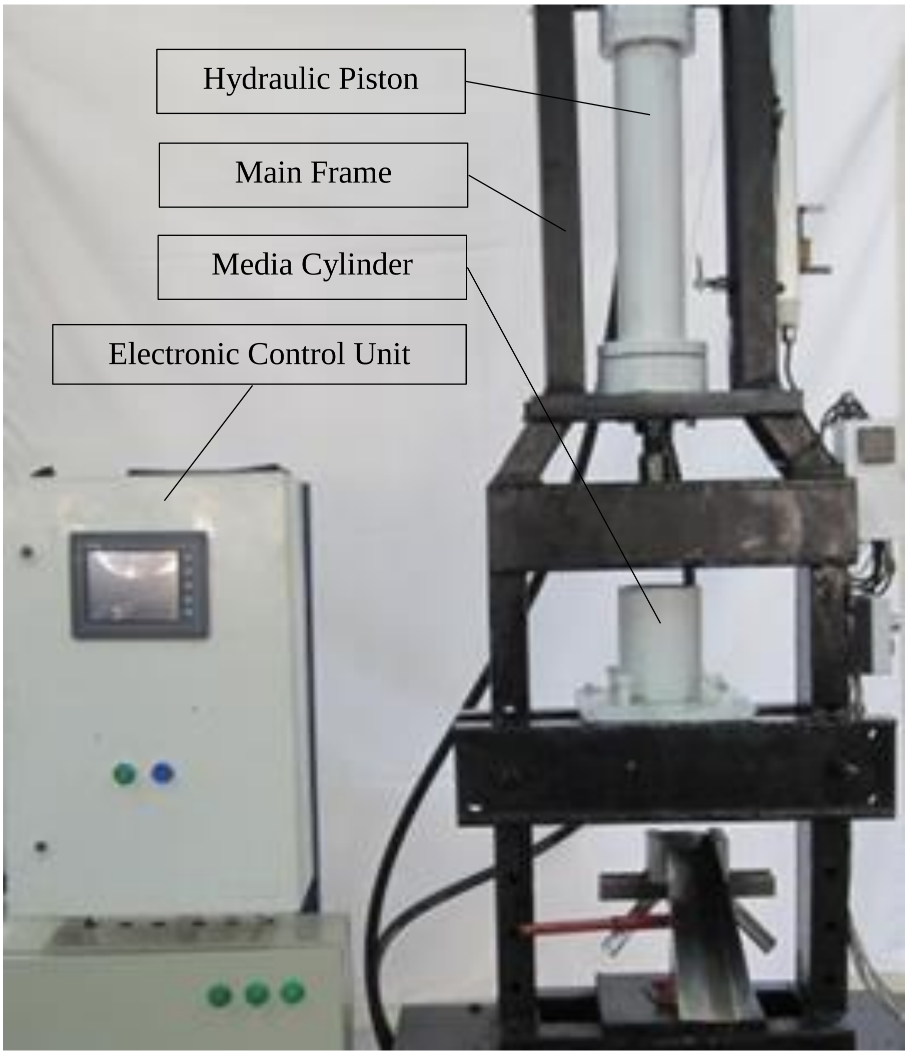


Figure 4.1 One-way AF machine

4.2.1.1 Hydraulic Unit

Hydraulic unit converts mechanical power to hydraulic power. They usually consist of an electric motor, fluid, pump, pipes, valves, reservoirs, and hydraulic actuators. The details of the unit are as follows:

Electric motor: a 10 kW electric motor is used to drive the pump.

Fluid: The most common hydraulic fluids contain specially compounded petroleum oils that lubricate and protect the system from corrosion. SAE 46 hydraulic oil is used.

Reservoir: Acts as a storehouse for the fluid and a heat dissipater. A metal tank of 80 litre is used as reservoir.

Hydraulic pump: converts the mechanical power into hydraulic power by forcing hydraulic fluid, under pressure and velocity, from the reservoir into the system. 100 bars hydraulic pump is used.

Fluid pipes: transport the fluid to and from the pump through the hydraulic system. These lines can be rigid metal tubes, or flexible hose assemblies. Fluid lines can transport fluid under pressure. Max 200 bars transmit flexible pipes are used.

Hydraulic Actuators: reconvert hydraulic power into mechanical power to do linear movement. Actuators usually take the form of hydraulic cylinders and perform the desired tasks. 100 mm internal diameter, 250 mm stroke distance hydraulic piston is used. The hydraulic unit is shown in Figure 4.2.

Figure 4.2 Hydraulic unit of one-way AFM

4.2.1.2 Electronic Control Unit

A PLC based control unit is designed to control the AFM process parameters. The control unit consists of a display which is used for monitoring and changing the process parameters, a PLC group that controls input and output parameters with respect to the given AFM parameters. The unit is shown in Figure 4.1.

4.2.1.3 Main Frame

Main frame is the base structure of the machine that was designed and constructed to house the hydraulic piston, the media cylinder, the hydraulic jack and all other components of AF machine. The main frame was joined by welding. 5x60x100 mm profiles were used.

The hydraulic piston and the media cylinder are fixed to the main frame by bolt-nut connection. The hydraulic jack is moveable on the bed of the main frame.

4.2.1.4 Workpiece Holder

The workpiece holder is designed and used to hold the 10x10x40 mm specimens allowing the flow of abrasive media through the workpiece surfaces with an opening of 2x20 mm. Two M6 screws are included on the workpiece holder to fix the workpiece as desired flow direction. The modelled 3D workpiece holder was machined by CNC milling machine from the 200x200x20 mm AISI 1040 steel as shown in Figure 4.3.

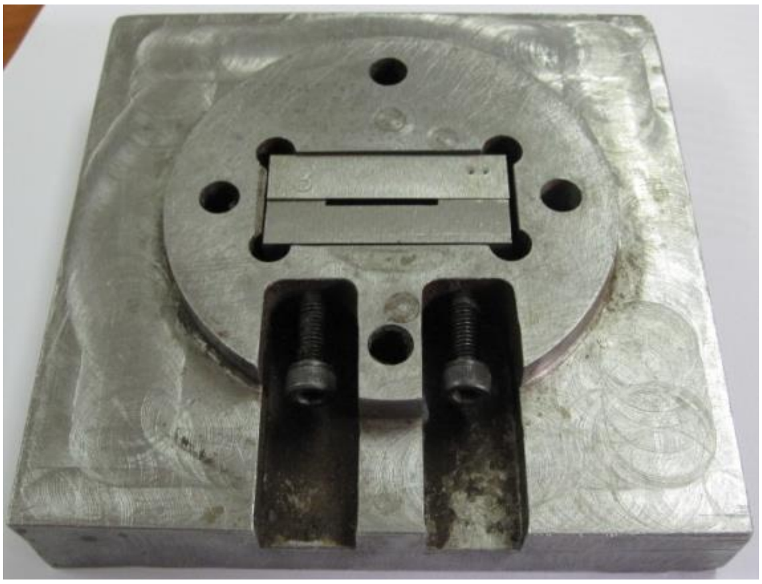


Figure 4.3 Workpiece holder

4.2.1.5 Media Cylinder

The media cylinder has two task: one is to house the abrasive media and the other is moving the pressurized abrasive media through the workpiece surface by the help of the workpiece holder and the conical nozzle. It is handled from commercial honed cylinder having 100, 140 mm in inner and outer diameters and 300 mm in length.

A 300x300x20 mm square plate was joined to the outer surface of the cylinder by arc welding to support the connection between the main frame and the media cylinder. The conical nozzle is connected to the lower end of the media cylinder.

4.2.1.6 Working Principle of One-way AFM Process

The hydraulic unit ensures adequate movement by using hydraulic piston's ram. The media is pressurized by the forward movement of the hydraulic piston's ram in the media cylinder. The electronic control system is designed to control the volume of abrasive media and the number of cycles. A cycle in one-way AFM is composed of the abrasive media filling stage of the media cylinder and completes stroke of the piston in 250 mm, then hydraulic piston is moved backward to the initial position, so that the cycle time can depend on the flow rate (i.e. piston speed) and one cycle in the experimental study can take about 1 minute. This combination of forward and reverse strokes completes one cycle of the AFM process. It is illustrated in Figure 4.4.

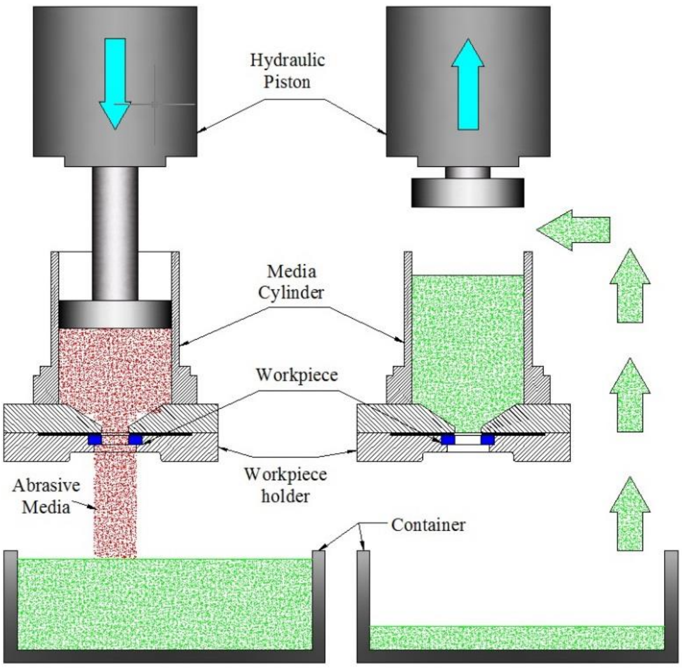


Figure 4.4 One-way AFM process

4.2.2 Two-way AF Machine

The common AF machines work in two-way principle. In this study a two way AF machine that has two vertically opposed chambers was designed and constructed. The machine contains two abrasive media cylinders, four hydraulic clamping pistons, two main actuating (main) pistons, a support and an electronic control system. A cooling-heating unit is also added to the AF machine.

The lower chamber having four clamping pistons is held stationary in the machine base although the other chamber, (in the head structure), moves vertically on guide of clamping pistons.

Each chamber contains a hydraulic piston and a ram on the tip of the piston to move and pressurize the abrasive media from one cylinder to the other. The electronic control unit adjusts the parameters and monitors the process data on the display. Also a cooling-heating unit added to the machine for keeping the abrasive media temperature constant. The design and constructed AF machine is shown in Figure 4.5 and Figure 4.6 respectively.

Figure 4.5 A photograph of two-way AF machine

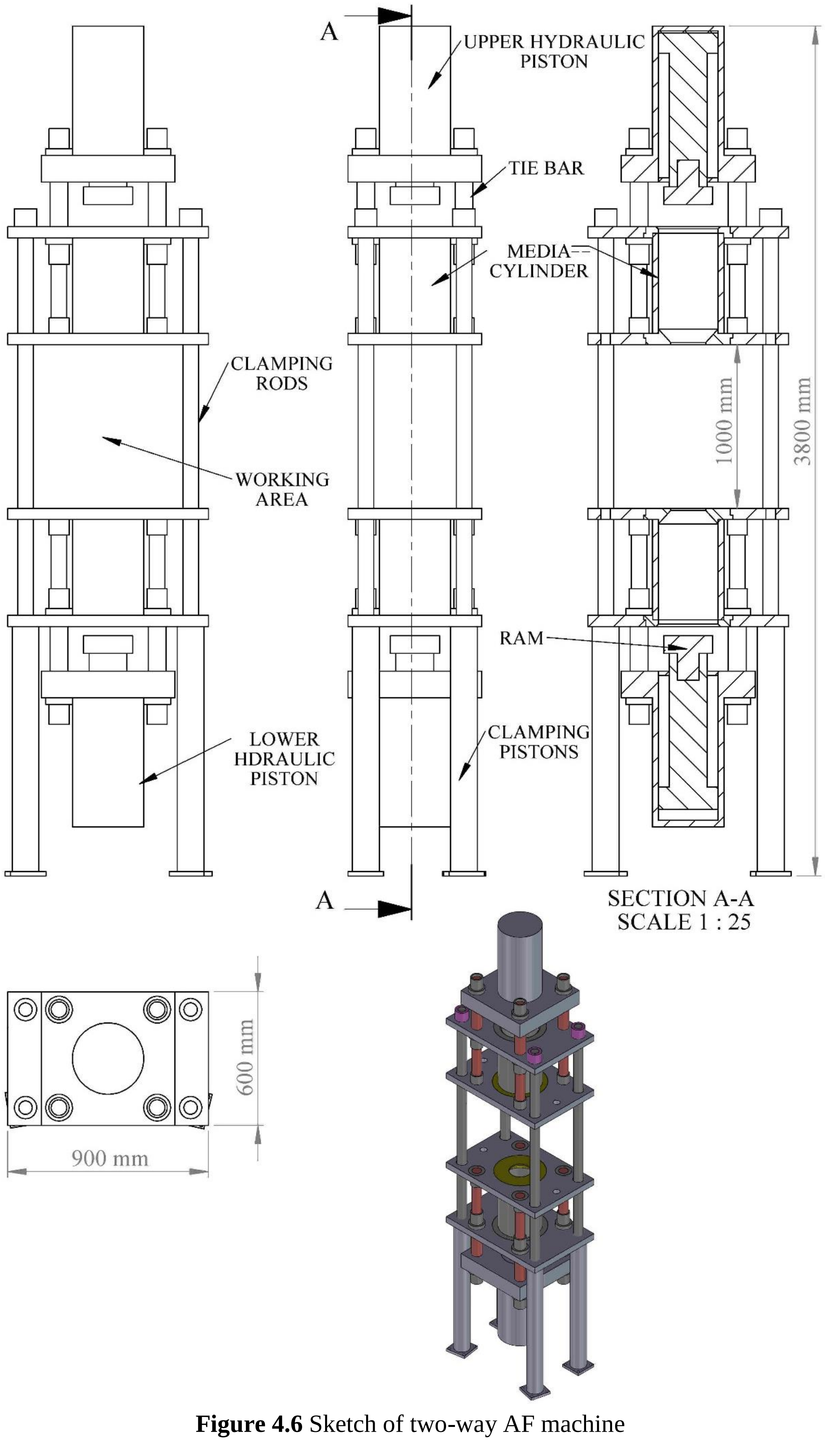


Figure 4.6 Sketch of two-way AF machine

4.2.2.1 Hydraulic Unit

Hydraulic unit is one of the most important unit for AF machines. The forward and backward movements cannot be well actuated without hydraulic unit.

An incompressible fluid is used in the hydraulic unit, to transmit pressure from one location to another. Hydraulic oil is pumped to a high-pressure level and transmitted throughout the machine via hydraulic piston then returns it to the reservoir. The oil is then filtered and re-pumped. The oil is controlled directly or automatically by the valves.

In this study, the hydraulic unit has specifications given in Table 4.1. The hydraulic unit of two-way AFM is largely the same as the one way AFM in section 4.2.1 but its capacity is higher and its valve system is different. The photo of hydraulic unit is shown in Figure 4.7. Some components different from the one-way AFM are as follows:

- The flow controls, one installed on each of the cylinder lines, to obtain the smooth flow of oil for each pistons and also to make the stroke of the cylinder rods constant.
- Hydraulic valves are hydraulically controlled valves which are opened or closed by aim of the pressure. They are directly mounted on the both ends of the main pistons for supporting the complex pistons movement.
- The solenoid valves are electrically controlled valves which are opened or closed by means of the electricity. They are mounted on the hydraulic flow block to adequate the all movements in hydraulic unit.

Table 4.1. Hydraulic Unit Properties for Two-way AF Machine

Components	Parameters	Items
Electric motor	22 kW	1
Hydraulic pump	Max 400 bars	1
Hydraulic oil	SAE 46	
Reservoir	500 litre	1
Fluid pipe	Flexible, max 600 bars	12
Hydraulic valve		1
Solenoid valve	10 Solenoid 24 V DC	10
Hydraulic piston	270 bore diameter, 400 mm stroke	2
Clamping piston	100 bore diameter, 1000 mm stroke	4

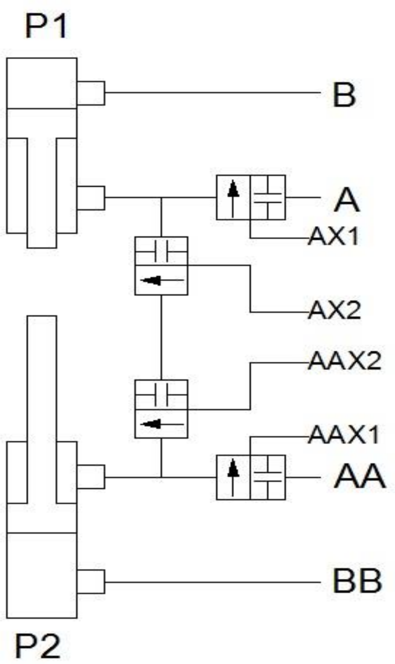
Figure 4.7 Hydraulic unit of two-way AFM

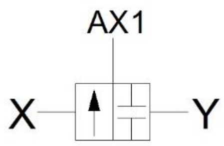
4.2.2.2 Electronic Control Unit

Figure 4.8 Electronic control unit

(1)	(7)	(8)	(9)	10
B	AX2	AA	AAX2	
Solenoid valves				
A	AX1	BB	AAX1	
(6)	(2)	(3)	(4)	5

(a) Solenoid connections





X	AX1	Y
1	1	1
1	0	0

(b) Schematic view of process

(c) Truth table of hydraulic valve

Figure 4.9 Hydraulic circuit of two-way AFM

		A (6)	B (1)	AX1 (2)	AX2 (7)	AA (8)	BB (3)	AAX1 (4)	AAX2 (9)	(5)	(10)
	Automatic forward		**1**		**1**	**1**			**1**		
	Automatic backward	**1**			**1**		**1**		**1**		
P1	Manual forward		**1**	**1**							
P1	Manual backward	**1**		**1**							
P2	Manual forward						**1**	**1**			
P2	Manual backward					**1**		**1**			
P1	One-way forward		**1**	**1**							
	One-way backward	**1**		**1**							
	Clamping open									**1**	
	Clamping close										**1**

Figure 4.10 Hydraulic circuit operation table

The two-way AFM process has a close loop control method. Process parameters such as number of cycle, abrasive media pressure and velocity of the flow are controlled according to the input sensors that are limit switches, pressure transducer and velocity measuring devices. These sensors are mounted on the main actuating pistons and hydraulic unit. All process parameters and control (constrains) parameters are set and monitored by using a 7 inch touchpad display. The unit is shown in Figure 4.8. The two-way AFM process is completed by means of the hydraulic operation table given in Figure 4.9 and Figure 4.10 respectively.

4.2.2.3 Main Frame

Beside differences in the working principle main frame is significantly different from the one-way machine. The main difference is that; one way machine is a construction of welded profiles on which the components are assembled whereas the two-way AF machine is composed of the assembly of the components. The main frame is mentioned in two chambers (lower or base and upper or head). The details of the chambers are as follows:

- Clamping pistons (section 4.2.2.3.1),
- Media cylinders (section 4.2.2.4),
- Main actuating hydraulic pistons (section 4.2.2.3.2),
- Ground plates: 50 mm in thick DIN 1050 steel was used to construct the chambers. Two plates were used for each chamber, also the clamping pistons are fitted to ground plate in the lower chamber.
- Upper and lower media cylinder rings: three sets of rings were produced by DIN 1050 steel to simplify the changing media cylinders.
- Tie bars (section 4.2.2.3.3),
- Nuts: twelve M70 nuts were produced from DIN 1050 steel to support the connections in each chamber. Eight nuts are used for constructing media cylinder assembly and four nuts are used to fit the main hydraulic piston to assembly of media cylinder in each chamber.

Firstly the media cylinder assembly was prepared by joining two plates, a media cylinder, two rings and four tie bars. Then the main hydraulic piston was fitted to this assembly by using four nuts tightened to the tie bars. In the lower chamber, four clamping pistons were connected to the plate from the barrel of the pistons by using eight M10 screws. Finally the upper media cylinder assembly was connected to the clamping piston-rod by fastening the M70 screws to the female threaded holes on the plate.

4.2.2.3.1 Clamping Pistons

The clamping pistons assembled in the lower chamber, have two functions; one is to feed the machine, the other is to clamp the workpiece holder. It has 100 mm inner and 140 mm outer diameter and 1000 mm stroke permits the finishing of the long dies. A flange with eight holes was welded to the front of the barrel, this flange supports the connection between the clamping pistons and the plate. The end of the piston-rod were threaded of M70 for connecting to the upper (head) chamber. (See Figure 4.11).

Figure 4.11 Clamping pistons

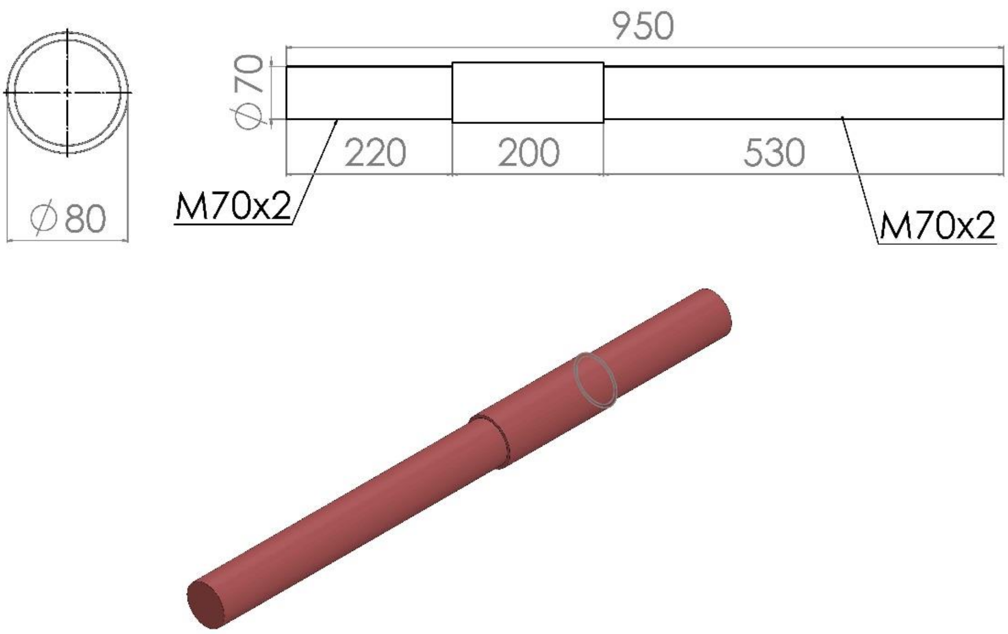
4.2.2.3.2 Main Hydraulic Pistons

Hydraulic piston is a mechanical actuator used to provide a rectilinear force through a linear stroke. It acquires power from pressurized hydraulic fluid, i.e. theoretically incompressible oil. The hydraulic piston consists of a cylinder barrel, in which a piston connected to a piston rod moves back and forth. The barrel is closed on both ends by the cylinder bottom and the cylinder head where the piston rod comes out of the cylinder. The hydraulic pressure acts on the piston to generate rectilinear motion. By pumping hydraulic oil to the bottom side of the hydraulic piston, the piston rod starts moving upward. The piston pushes the oil in the other side back to the reservoir. If the oil is pumped into the piston rod side and the oil from the piston side flows back to the reservoir. In this way the main hydraulic piston can operate both forward and backward motion.

A 100 mm thick flange with four holes was welded to the front of the barrel, this flange supports the connection between the media cylinder assembly and main hydraulic piston. Each chamber has a hydraulic piston having the dimensions of 270 mm inner, 320 mm outer diameter and 400 mm stroke, to supply the movement of the AFM process which is the extrusion of the abrasive media through or over the workpiece. The end of the piston rod is threaded with M120 screw. The rams which were produced in three different outer diameters for supporting the different media cylinder sizes have internally threaded holes with M120 for connection between ram and piston rod. The main actuating piston is shown in Figure 4.12.

Figure 4.12 Main hydraulic piston

(a) Media cylinder assembly



(b) Tie bar

Figure 4.13 (a) Media cylinder assembly, (b) Tie bar

4.2.2.3.3 Media Cylinders

Three sets of media cylinders were produced by using commercially available honed cylinders. The capacity of the media cylinders was defined according to three objectives. Firstly, an abrasive media of 6 litre capacity was defined, for experiments. All the experiments were carried out using these media cylinders. The second one is media capacity of 10 litre of abrasive media. The last one is defined for industrial applications, it has 23 litre abrasive media capacity. All media cylinders were covered and welded 20 mm apart from the outer surface by using 2 mm thick AISI 304 chromium sheet metal. A shell (jacket) was produced to accept the fluid flow around the media cylinders. This fluid keeps the abrasive media temperature constant during AFM process.

The essential function of media cylinder is to retain the abrasive media and to support the movement of the pressurized abrasive media through the workpiece surface. Two sets of media cylinders are shown in Figure 4.15.

Two rings are mounted the upper and bottom sides of the media cylinder, then this group is fixed between the two ground plates by means of the tie bars, finally this assembly is connected to the main hydraulic piston. The assembly of the media cylinder is shown in Figure 4.13(a).

4.2.2.4 Workpiece Holder

The workpiece holder is used to restrict and direct the flow of the abrasive media to the appropriate areas of the workpiece. It is designed and used to hold the specimens (10x10x40 mm) allowing the flow of polishing media through the workpiece surfaces with an opening of 10x20 mm. It consists of five parts; two parts are conical nozzles which are assembled upper and lower of the workpiece holder. The workpiece holder can hold ten workpieces together by means of the twenty M6 screws (Figure 4.16).

4.2.2.5 The Heating and Cooling Units

Heating and cooling units are used for providing desired abrasive media temperature. It consists of two main sections: heating, and cooling sections (Figure 4.14). The cooling unit includes many parts such as compressor, evaporator, condenser, fans, water reservoir, thermostats and centrifugal pump. The heating unit consists of resistance heater, water reservoir, thermostat and centrifugal pump.

Figure 4.14 Heating and cooling units

Figure 4.15 Media cylinders

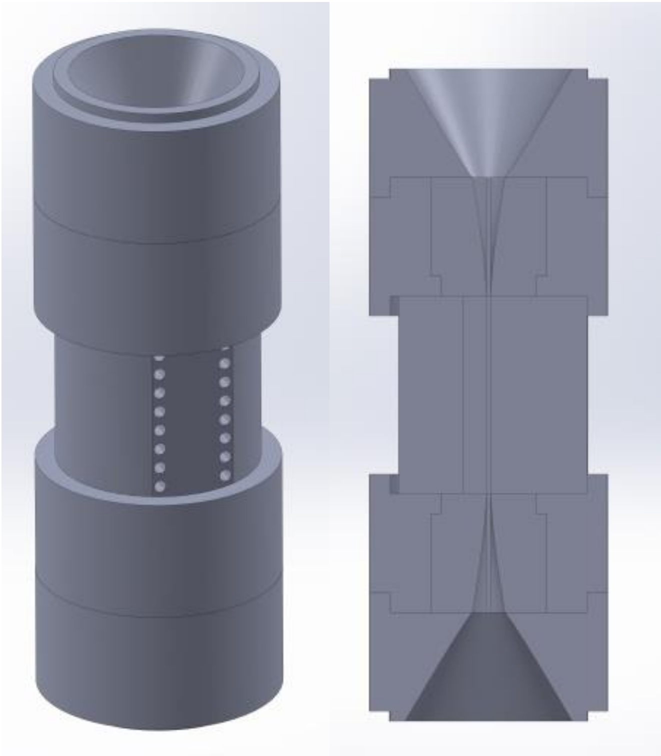


Figure 4.16 The workpiece holder

The water is cooled or heated up to desired temperature in the water reservoir by means of the cooling or heating unit. Then this water is pumped through the media cylinder jackets by using pipes. This circulation continues during the AFM process.

4.2.2.6 Working Principle of Two-way AFM Process

A complete cycle of two-way AFM is as follows:

1. The two actuating pistons are moved to their home positions, the lower piston-ram is positioned at the back of the lower media cylinder. The upper actuating piston-ram is positioned in front of the upper media cylinder with the aid of the limit switches,
2. The abrasive media is filled to the lower media cylinder at desired volume,
3. The workpiece holder group is placed between the upper and lower media pistons,
4. The workpiece holder group clamped by using four clamping pistons,
5. The velocity of the abrasive media and the number of process cycle are set on the electronic control unit,
6. Process is started in desired number of cycle and velocity,

The lower actuating piston extrudes the abrasive media from the lower to the upper media cylinder through the workpiece surfaces simultaneously the upper actuating piston moves backward. After completing the upward movement, the upper actuating piston extrudes the abrasive media from the upper to the lower media cylinder through the workpiece surfaces. When the pistons reach the limit switches one cycle is completed.

7. After reaching to desired number of cycles, the clamping pistons open the upper and lower plates,
8. The workpiece holder group taken away from the machine and disassembled.

This process is illustrated in Figure 4.17.

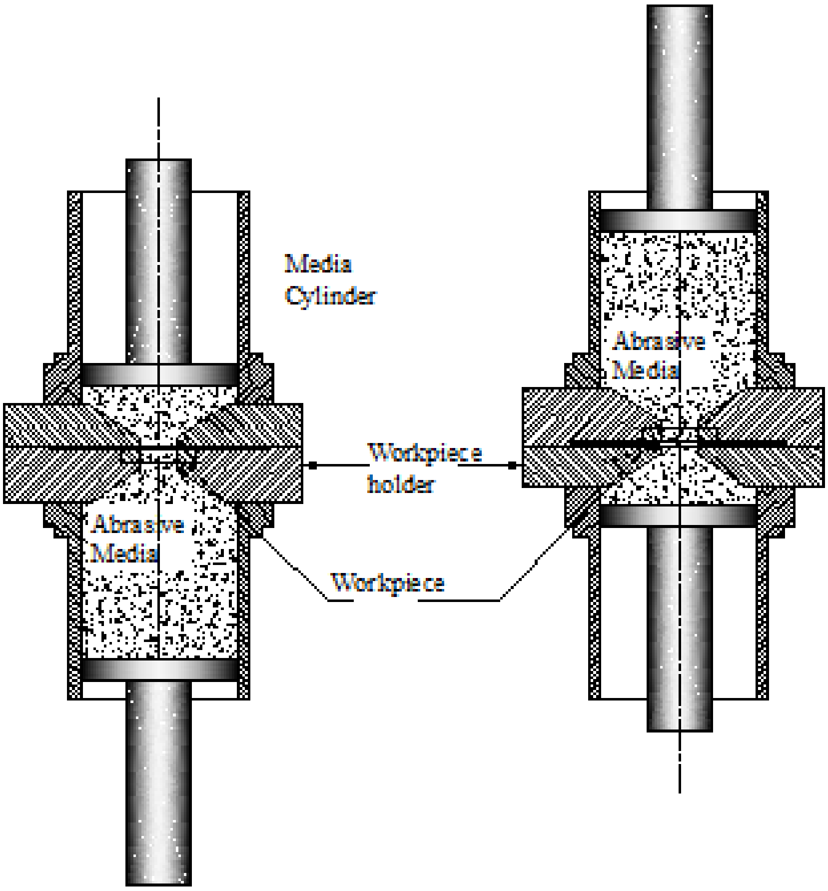


Figure 4.17 Two-way AFM process

CHAPTER 5

EXPERIMENTAL STUDY

5.1 Introduction

The experimental studies are explained in this chapter. These studies are performed to investigate the effects of various AFM process parameters on the performance parameters of EDMed surface.

Section 5.2 explains preliminary experiments that done using a primitive set up, which was modified from a conventional lathe.

Section 5.3 includes detailed descriptions of the equipment and instrumentation used in these experiments. Section 5.4 gives the explanations of the experimental procedure.

5.2 Preliminary Experiments

A primitive AFM set up modified from a conventional lathe was developed to investigate and understand the basic AFM process parameters such as number of cycle, abrasive concentration and media velocity. The workpiece holder was assembled between the two media cylinders, and then this assembly was bolted to the lathe carriage system. The carriage was driven by using transverse feed system of the modified lathe, so that the velocity can be adjusted. The rams were connected to chuck and tailstock of the lathe shown in Figure 5.1. The process was controlled manually. Ground AISI 1050 carbon steel was used as workpiece material. The results show that higher material removal (MR) and better improvement in surface were obtained by increasing abrasive concentration. However, the abrasive concentration higher than 70% choked the setup and the abrasive media could not adequately flow through the workpiece surface [86].

Figure 5.1 Primitive AFM set up by using lathe machine

The majorities of the AFM studies are identified by means of the preliminary experiments as follows;

- Identifying and investigating the AFM process parameters,
- Identifying the AFM performance parameters,
- Developing an abrasive media,
- To design and construct a AFM machine,
- Specifying the measuring instruments,
- Specifying the pre-machining conditions,
- Specifying the target industry.

According to the above topics, two AF machines were designed and manufactured to evaluate the AFM process and performance parameters. The EDMed surfaces are suggested for AFM studies and die-mould industry is chosen as target industry. For example an extrusion die is shown in Figure 5.2.

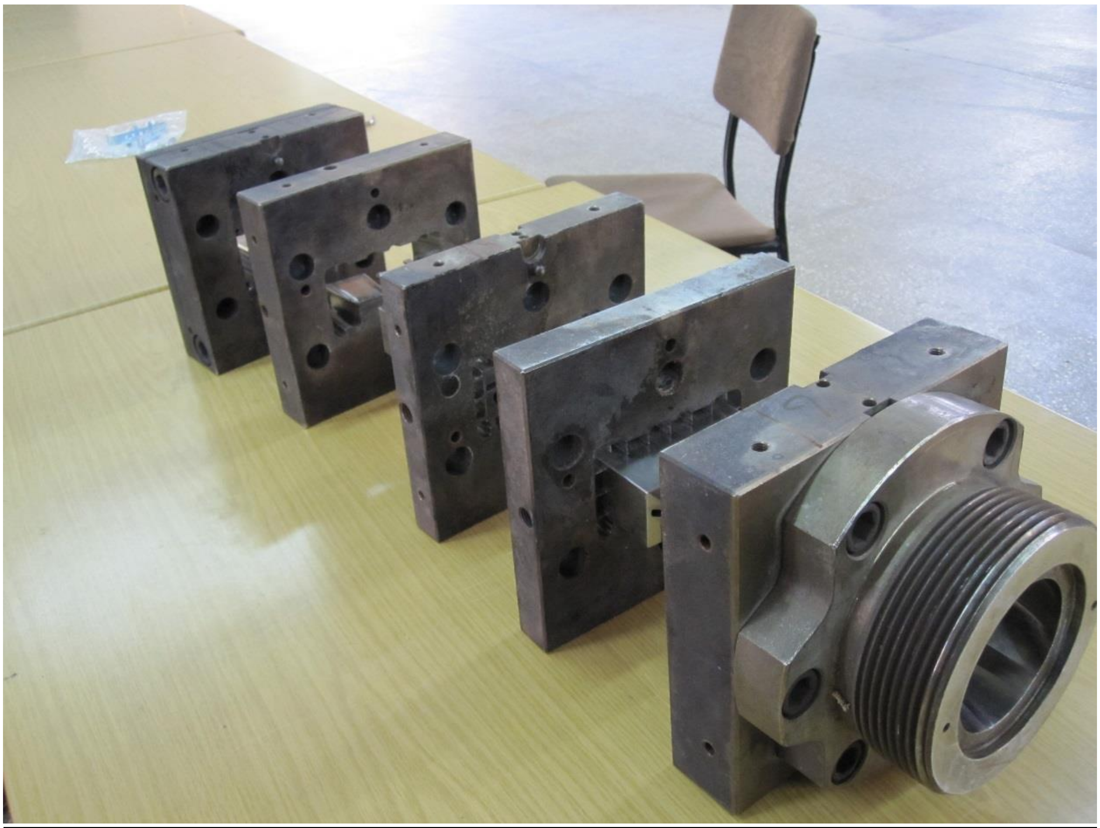


Figure 5.2 Parts of an extrusion die assembly

5.3 Equipment and Instrumentation

The main equipment used in the experimental study is explained in this section, and measuring instruments are also given.

5.3.1 Machine

To perform the experiments, two AFM machines were used. The design and manufacturing details were explained in Chapter 4. Here, the specifications of the machines used in experimental work are given.

5.3.1.1 One-way AF Machine

A one-way AFM, as shown in Figure 4.1, was designed and constructed to perform the experiments. The machine is composed of a hydraulic unit, a main frame, a workpiece holder, a media cylinder and a hydraulic piston.

A conical nozzle is fixed to the bottom end of the media cylinder then the workpiece holder is assembled to the open end of the nozzle to obtain a uniform flow of the abrasive media and maximum improvement on the workpiece surface. The specifications of the machine are given in Table 5.1.

Table 5.1. One-way abrasive flow machine specifications

Machine Specification	
Pump Pressure	24 – 200 bars
Media capacity	2 litre
Stroke	250 mm
Bore diameter	120 mm

5.3.1.2 Two way AF Machine

A two way AF machine shown in Figure 4.5 was designed and constructed in the study. The specifications of the machine are given in Table 5.2. The machine is composed of a hydraulic unit, a main frame, an electronic control unit and a heating-cooling unit.

Table 5.2. Two-way abrasive flow machine specifications

Machine Specification	
Pump Pressure	24 - 400 bar
Media capacity	6-10-23 litre
Stroke	400 mm
Bore diameter	140-180-280 mm

5.3.2 Abrasive Media

A new abrasive media was developed by the supervisor and the author of the thesis performed the experimental studies. The media is composed of a base polymeric carrier and the abrasive particles. Frequently, some additives may be used in the abrasive media. The abrasive media is prepared by mixing abrasives and the polymeric carrier in a required amount. The abrasive particles are held in the polymeric carrier in uniform dispersion. The uniform distribution of the abrasive particles in the mixture is important.

5.3.2.1 Polymeric Carrier

Polymeric carrier is a viscoelastic polymer since it exhibits both flow and elasticity. This apparent viscoelasticity permits the polymeric carrier to behave as a semi-solid viscous fluid. That is, at restrictions in its flow path the viscosity of the polymeric carrier increases and the flow becomes more "solid" ; however, once the restriction is passed its viscosity returns to its original value and the flow becomes similar to that of a fluid once again.[13].

The polymeric carrier conforms exactly to the part geometry insuring 100 percent contact on all surfaces that it flows through or over. The polymeric carrier also has good cohesion and little tendency to adhesion. Therefore it tends to "fuse" to itself and remains as a coherent entity during process. Moreover to alter the polymeric carrier viscosity plasticisers or reducers may be added, the viscosity being determined by the ratio of polymer to diluent.

5.3.2.2 Abrasives

Silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C), and garnet abrasives were used in these experimental studies. Silicon carbide (SiC) is the most widely used abrasive in the AFM process since it lasts longer and is cheaper than the others. Aluminium oxide (Al_2O_3) is also used in a variety of applications, since it performs well, but is used less frequently than silicon carbide due to its cost. The boron carbide (B_4C) which has the highest cost among others, is only used to machine very hard materials. Garnet is also used in our experiments as an abrasive in the AFM media. This is first in literature and can be preferred for its low cost. The physical and chemical properties of these abrasives are given in Table 5.3.

5.3.3 Surface Roughness Measurements

Surface roughness is one of the significant performance parameter of our experimental study. The surface roughness parameters R_a, R_t and R_q were measured before and after AFM process of each specimen. The measurements were taken in direction perpendicular to the AFM flow lines and 18 measurements located at the positions with a distance of 0.5 mm were taken for each specimen (see Figure 5.3). Mitutoyo SJ

401 surface measuring machine as shown in Figure 5.4 was used with a cut of length 0.8 mm for all experiments.

Table 5.3. Abrasive properties

		B_4C	SiC	Al_2O_3	Garnet
Mesh size		180	180	180	180
Hardness	Mohr	9,5	9	9	7,5-8
Density	gr/cm^3	2.52	3.2	3.7	4.1
Apparent density	gr/litre	1200	1500	1800	2200
Price	$/tons	10000-35000	1000-1700	800-1000	100-250

5.3.1 Material Removal Measurements

Material removal is another significant performance parameter in AFM process. It is calculated as the difference between the initial and final weights of the specimen. SHIMADZU AUX220 balance having 0.1 mg accuracy is used in these experiments as shown in Figure 5.5.

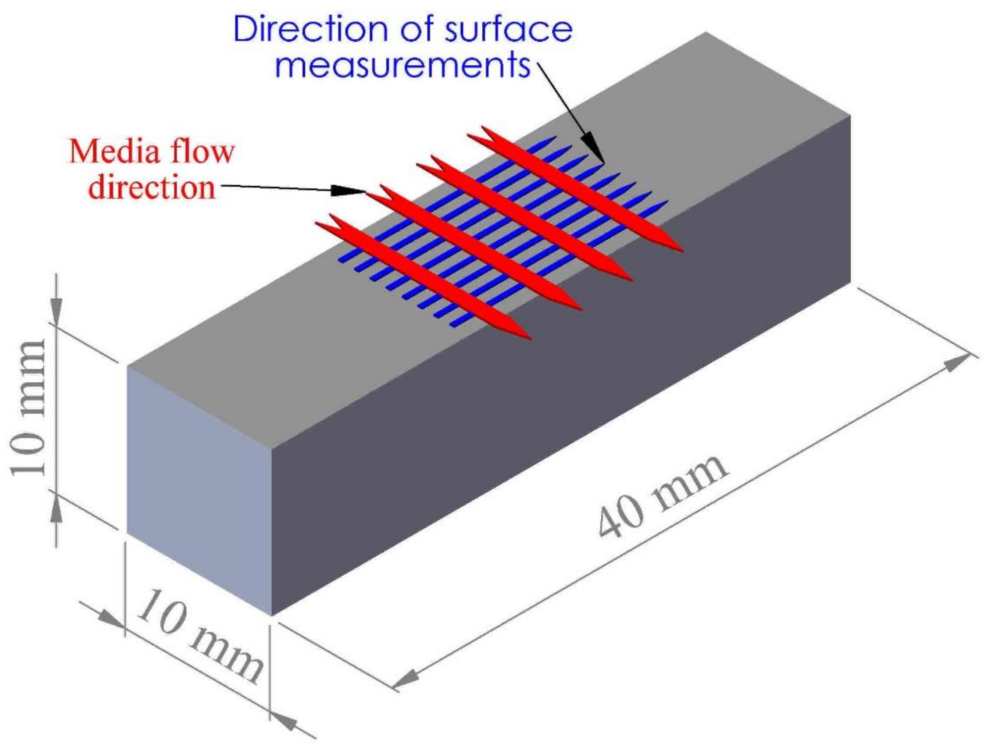


Figure 5.3 Surface roughness measurement lines on the specimen

Figure 5.4 The surface roughness measuring machine

Figure 5.5 Shimadzu AUX220 balance

5.3.2 SEM Images

One of the objectives of this thesis is to improve the surface quality of EDMed surface by AFM process. Therefore, the workpiece surface must be well studied, not only material removal (MR) and surface roughness but also SEM images were taken for this purpose. The images were compared before and after AFM process by means of the JEOL JSM-6390 LV electron microscopy shown in Figure 5.6.

Figure 5.6 Scanning electron microscopy, SEM

5.3.3 Viscosity Measurement

Viscosity is a fundamental property of all liquids. As a liquid flows, it subjects to an internal resistance to flow. Viscosity is a measure of this resistance to flow or shear. Viscosity is a function of both temperature and pressure.

The developed media's rheological properties were described with and without abrasive particles by using Thermo Scientific rheometer (see Figure 5.7) which is available in Food Engineering Department of Gaziantep university.

Figure 5.7 Rheometer

Figure 5.8 Optical microscope

5.3.4 Microscopic Views

To examine the thickness and distribution of the white layer on the EDMed surface, the section view of workpiece must be analysed. The etched section of the workpiece was examined using Nikon eclipse MA 100 optical microscope. (Figure 5.8).

5.4 Experimental Procedure

In this section the experimental procedures are explained.

5.4.1 Experiment 1

This experiment was designed to investigate the effects of AFM process parameters such as number of cycles, abrasive mesh size, and abrasive concentration on the surface roughness. Also pre-machining conditions produced by WEDM as rough and finish were examined. The one way AF machine was used for this experiment.

5.4.1.1 The Workpiece Material

The experiments were performed on DIN 1.2080 cold-work tool steel. The specimens were cut from 10 mm to 40 mm slab by using wire EDM to 10x10x40 mm in size. The wire EDM parameters were properly selected to obtain a surface roughness of R_a =4.6 μm and R_a =2.6 μm for rough and finish cuts, respectively.

5.4.1.2 The Abrasive Media

The media used for experiment 1 is a mixture of polymeric carrier, silicon carbide abrasive particles, and hydraulic oil. The abrasive particles (SiC) of specified mesh size and amount are used to achieve the desired weight ratio. However, the common definition of the percentage abrasive concentration is given by: weight of abrasive particles x 100/ (weight of media). Before performing the experiments, the abrasive media is run for 3–5 cycles with a trial workpiece, so as to achieve a uniform mixing.

5.4.1.3 The Experimental Procedure

Based on the conclusions from the preliminary experiments, four important variables are identified, namely the number of cycle, abrasive concentration, abrasive mesh size, and pre-machining conditions (rough and finish). The experiments were performed at the values given in Table 5.4.

Table 5.4. Experimental Parameters

Variable parameters	**Value**
Abrasive mesh size	100-180-240
Abrasive concentration	50 %-70 %
Number of cycles	1-3-5-10-20-30-40-60
Constant parameters	
Piston velocity	900 mm/min
Pressure	64 bar
Volume of the media flowing in one cycle	1.5 litre

After reaching the desired number of cycle, the workpiece is taken out from the workpiece holder and cleaned with alcohol before any measurement is done.

5.4.2 Experiment 2

This experiment is performed to investigate the workpiece hardness effects on abrasive flow machining process. However, there is only one study available in the literature [12] considering the effect of hardness of the workpiece material. But this study [12] was carried out for brass and aluminium as hard and soft material, respectively. Therefore, it is necessary to show the hardness effects of the steel on the AFM process. This experiment is focused on the effect of workpiece hardness on the AFM process. The initial surface roughness values of each hardness group workpiece are given in Table 5.5. The one way AF machine was used for the experiment.

5.4.2.1 The Workpiece Material

The workpiece is made of the heat treated DIN 1.2379 tool steel. 10x40x500 mm slabs were cut from the same stock and heat treated to 31, 45 and 55 HRC. The specimens were cut from the slabs by using wire electro discharge machine (WEDM) to 10x40x10 mm. The WEDM parameters kept constant for all specimens to ensure the pre-surface characteristics of the specimens. The surface roughness values of the specimens after WEDM are given in Table 5.5 (R_a, R_z, R_q).

Table 5.5. Surface roughness values of the specimens before AFM

Hardness	Specimen no	R_a (µm)	R_z (µm)	R_q (µm)
31 HRC	A13	2.5	10.34	2.96
	A14	2.4	12.88	2.52
	A15	2.4	11.42	2.48
	A16	2.5	10.09	2.61
	A17	2.5	9.17	2.84
	A18	2.5	12.33	3.19
45 HRC	B13	2.4	14.20	2.85
	B14	2.6	11.93	2.42
	B15	2.4	11.50	2.38
	B16	2.6	9.34	2.93
	B17	2.4	8.49	2.77
	B18	2.4	10.42	2.11
55 HRC	C13	2.4	12.05	3.02
	C14	2.6	11.65	2.57
	C15	2.4	12.19	2.52
	C16	2.4	9.90	2.75
	C17	2.4	10.00	2.88
	C18	2.5	12.11	3.14

Table 5.6. Abrasive media parameters

Parameters	
Viscosity	60 Pas
Abrasive type	Al_2O_3
Mesh size	180
Abrasive concentration	70 % wt.

5.4.2.2 The Abrasive Media

The abrasive media used for this experiment is a mixture of polymeric carrier, 180 mesh size aluminium oxide (Al_2O_3) abrasive particles, and hydraulic oil. The abrasive media was prepared in a definite proportion to achieve a 70% concentration of abrasive particles by weight. The specifications of the media are summarized in Table 5.6.

5.4.2.3 The experimental procedure

The experiments were performed on the three groups of specimens (31, 45 and 55 HRC). A fixture (see **Figure** 4.3) was used to hold the specimens allowing the flow of abrasive media through the WEDMed surfaces with an opening of 2x20 mm. 2000 g of abrasive media was flowing through in one cycle and the experiments were carried out for 1,3,5,10,20 and 100 cycles, respectively. The AFM pressure was 10 MPa and its flow rate was 50 g/s. The experiments were repeated for three specimens in each condition and the averages of the 18 surface roughness measurements were taken. Mitutoyo SJ 401 surface measuring machine was used and the cut off length was chosen as 0.8 mm. The SEM images of the surfaces were taken using Jeol JSM-6390 LV.

5.4.3 Experiment 3

Effects of different abrasives on AFM process were investigated in this experiment. Silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C), and Garnet were used as abrasives. Number of cycle was selected as AFM process parameter which affects the performance parameters such as the surface roughness and material removal (MR). The two-way AFM machine was used for this experimental study.

5.4.3.1 The Workpiece Material

Two groups of specimens were prepared from DIN 1.2379 cold-work tool steels. 10x40x500 mm slabs were cut from the same stock. One group of DIN 1.2379 heat treated to 55 HRC, other stay as bulk hardness of 15 HRC. The specimens were cut from the slabs by using wire electro discharge machine (WEDM) to 10x40x10 mm. The WEDM parameters were kept constant for all specimens to ensure the pre-surface characteristics of the specimens. The surface roughness values of the specimens after WEDM are given in Table 5.7.

Table 5.7. Surface roughness values of the specimens before AFM

	Specimen No	R_a (µm)	Specimen No	R_a (µm)	Specimen No	R_a (µm)	Specimen No	R_a (µm)
55 HRC	S1	2.78	A1	2.65	B1	2.58	G1	2.88
	S2	2.44	A2	2.62	B2	2.87	G2	3.10
	S3	2.22	A3	2.69	B3	2.89	G3	2.66
	S4	2.13	A4	2.89	B4	2.78	G4	3.12
	S5	2.66	A5	2.54	B5	2.69	G5	2.69
	S6	2.49	A6	2.78	B6	2.79	G6	2.89
15 HRC	1	3.78	8	3.40	8	3.56	22	3.28
	2	3.44	9	3.87	9	3.58	23	3.36
	3	3.22	10	3.91	10	3.49	24	4.74
	4	3.13	11	3.94	11	3.41	25	3.65
	5	3.66	12	3.62	12	3.68	26	3.62
	6	3.49	13	3.38	13	3.34	27	3.70

Table 5.8. Abrasive media parameters for Experiment 3

Parameters	
Viscosity	60 Pa.s
Abrasive type	SiC, Al_2O_3, B_4C and Garnet
Mesh size	180
Abrasive concentration	70 % wt.

5.4.3.2 Abrasive Media

For this experiment, the abrasive media is prepared by mixing the polymeric carrier, hydraulic oil and abrasive particles such as silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C) and Garnet. The specifications of the media are summarized in Table 5.8. The properties of the abrasives used in this experiment are given in Table 5.3.

5.4.3.3 Experimental Procedure

The experiments were performed in the four groups of specimens. A fixture (see Figure 5.9) was used to hold the specimens allowing the flow of abrasive media through the WEDMed surfaces with an opening of 10x20 mm. 12 litre of abrasive media was flowed in each cycle and the experiments were carried out for 1,3,5,10,20 and 50 cycles. The AFM pressure was 10 MPa and its flow rate was 10 litre/min. The experiments were repeated for three specimens in each condition and the averages of three surface roughness measurements were taken by using Mitutoyo SJ 401 surface measuring machine, with the cut off length of 0.8 mm. The specimens were weighed before and after the experiment by using SHIMADZU AUX220 balance.

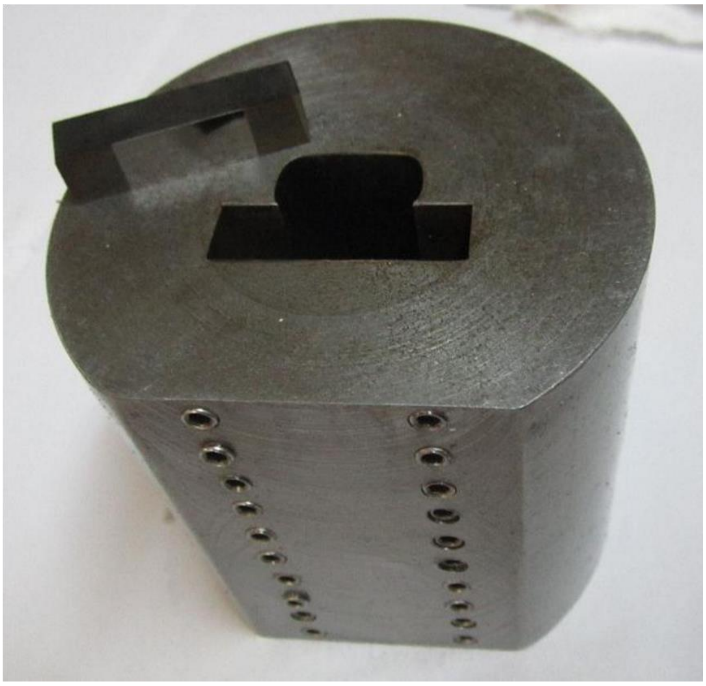


Figure 5.9 The workpiece holder

5.4.4 Experiment 4

This experiment is performed to investigate the effects of AFM process parameters on the surface roughness (R_a) of commercial pure titanium (Grade 1). However, there is only one study available in the literature [87], and it was carried out for micro holes. The one way AFM machine was used for this experiment.

5.4.4.1 Workpiece Material

The experiments were performed on Titanium (Grade 1). The specimens were cut from the slabs by using wire electro discharge machine WEDM to 5x10x20 mm as shown in Figure 5.10. The WEDM parameters were kept constant for all specimens to ensure the pre-surface characteristics of the specimens. The surface roughness values of the specimens after WEDM were 2.8 μm and 3.4 μm R_a. The chemical composition of titanium (Grade 1) is given in Table 5.9.

Figure 5.10 Titanium workpiece

Table 5.9. Chemical composition of titanium Grade 1

Component	Wt. % Max
C	0.1
Fe	0.2
H	0.015
N	0.03
O	0.18
Ti	99.5

5.4.4.2 Abrasive Media

The abrasive media that was prepared for the present study is a mixture of polymeric carrier, silicon carbide (SiC) abrasive particles, and 10% of hydraulic oil. The polymeric carrier has specific gravity of 1.0 (at 25 ^{o}C) and viscosity about 60 Pas. 100,180 and 240 mesh size silicon carbide (SiC) abrasives of 40% and 70% ratios by weight were used. The specifications of the abrasive media are summarized in Table 5.10.

Table 5.10. Abrasive Media parameters

Parameters	
Viscosity	60 Pas
Abrasive type	SiC
Mesh size	100,180 and 240
Abrasive concentration	40 % and 70 % wt.

5.4.4.2.1 Experimental Procedure

The experiments were performed on the commercial pure titanium (Grade 1) The workpiece holder (see Figure 4.3) was used to hold the specimens allowing the flow of abrasive media through the WEDMed surfaces with an opening of 2x20 mm. 2000 g of abrasive media was flown through in each cycle. The experiments were carried out for 1, 3, 5, 10, 20, 60, 80 and 100 cycles. The AFM pressure was 10 MPa and flow rate was 3000 g/min. The experiments were repeated for three specimens in each condition and the averages of five surface roughness measurements were taken. The SEM images of the surfaces were also observed.

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 Introduction

This chapter presents the results and discussions of the experiments described in Chapter 5. Each section includes a presentation of the experimental data and detailed analysis of the results. Tables and figures are given to further help the reader to interpret the results.

6.2 Experiment 1

The effects of various AFM process parameters such as number of cycle, abrasive mesh size and abrasive concentration on surface roughness (R_a) value are reported in this section.

6.2.1 Effect of Number of Cycle

The experimental study was carried out for understanding the effects of number of cycle on surface roughness (R_a), it is performed by 100 mesh size SiC abrasive and 50 percent abrasive concentration on the rough cut surface. The initial surface roughness value (R_a) is about 4.5 μm, after the 60 cycles it decreases to 0.5 μm. Preliminary experiments show that the number of cycles has significant effects on surface roughness.

Figure 6.1 shows that as the number of cycles increase, the surface roughness decreases. The experiment also demonstrates that a higher decrease in surface roughness (R_a) value in earlier stages of the process about 15 cycles than for the rest of the process. This can be explained as large number of peaks and valleys which exist on the workpiece surface so AFM reduces these peaks within the first few cycles. Removing these peaks causes less decrease in surface roughness (R_a) value in the following cycles.

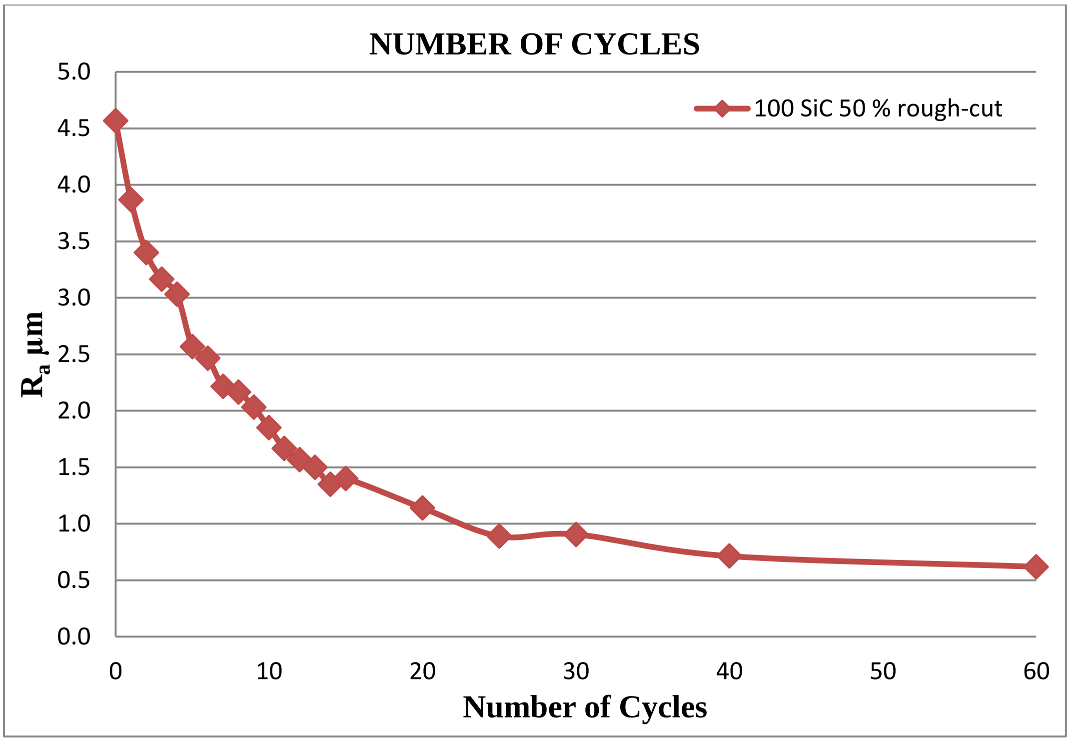


Figure 6.1 The effect of the number of cycles on the surface roughness (R_a)

6.2.2 Effect of Abrasive Concentration

The experimental study was performed by using two different abrasive concentrations to examine the effect of the concentration on the surface roughness improvement in AFM process. The abrasive concentrations were taken as 50% and 70% by weight. Figure 6.2 indicates that with the increase in concentration of abrasive in polymeric carrier for different numbers of cycles, the surface roughness (R_a) value decreases. The more improvement in surface roughness can be explained with a higher concentration, more abrasive particles come into contact with the workpiece surface resulting in more abrasion, hence higher improvement in R_a.

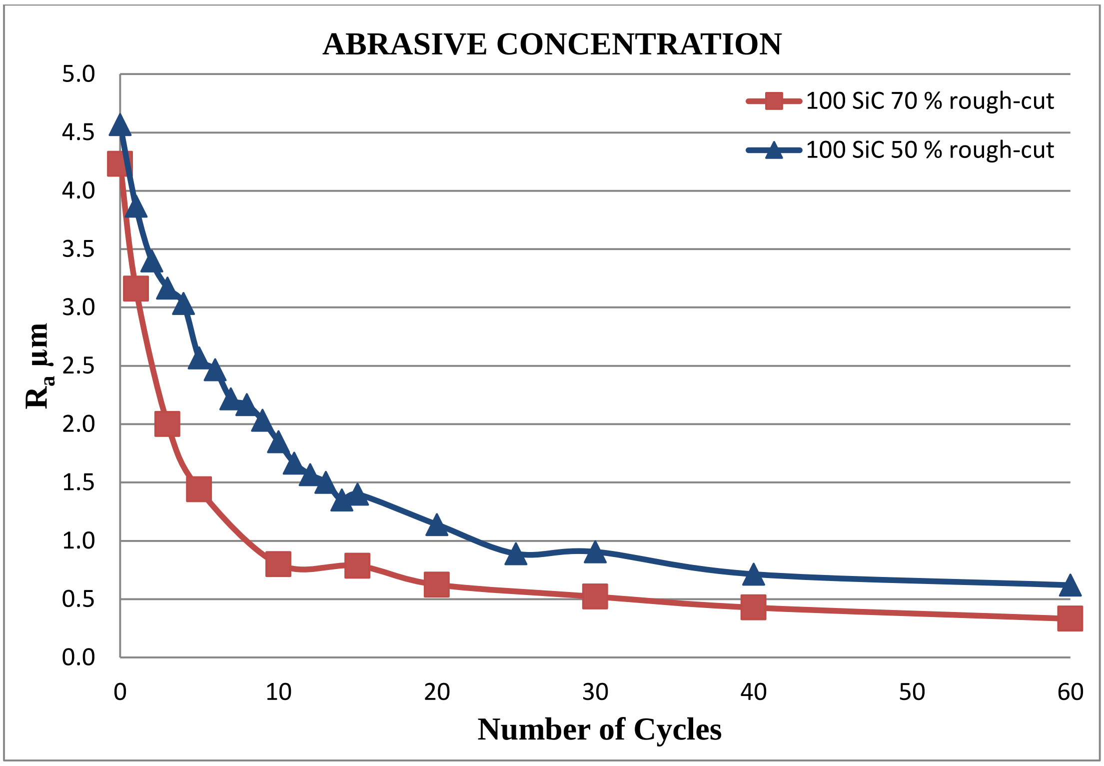


Figure 6.2 The effect of abrasive concentration on the surface roughness (R_a)

6.2.3 Effect of Abrasive Mesh Size

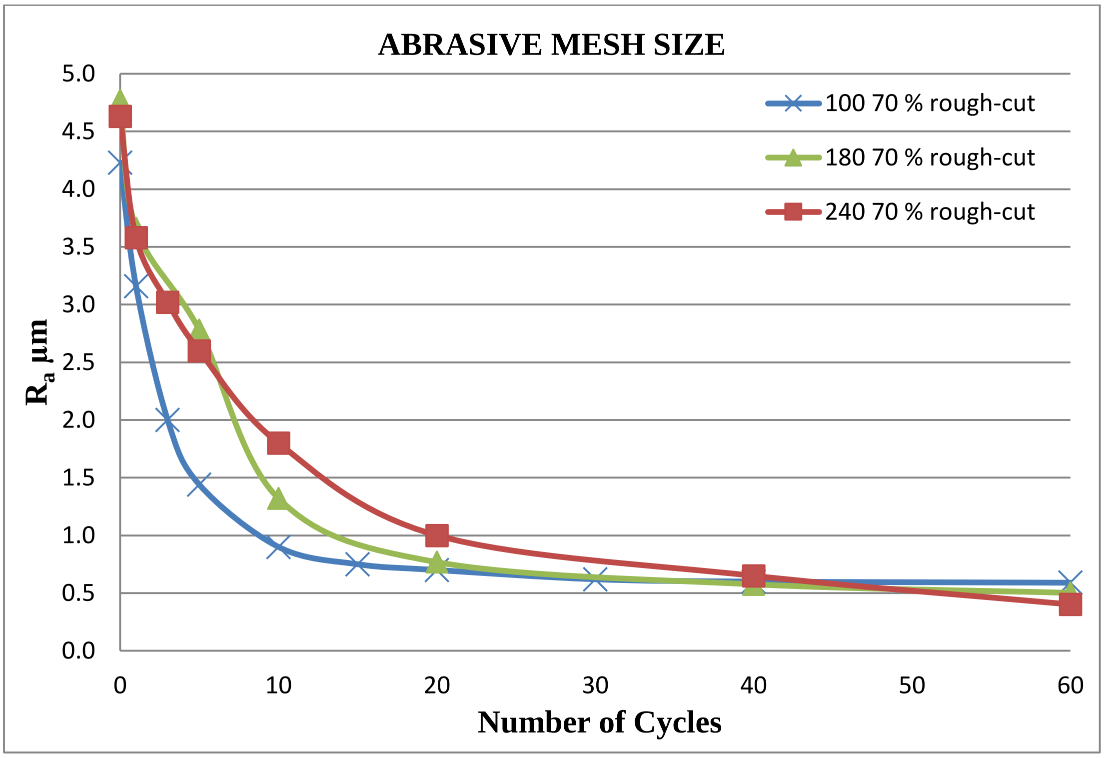


Figure 6.3 The effect of the mesh sizes on the surface roughness (R_a)

The second significant AFM process parameter is the abrasive grain size which determines the depth of finishing, so as the material removal and the final surface roughness. The experimental study was performed by using 100, 180 and 240 mesh sizes to examine the effect of the mesh sizes on the surface roughness in AFM process. Figure 6.3 shows the results of abrasive mesh size on the surface roughness.

The finer grain size (larger mesh size 240) results in more (better) surface improvement (lower R_a) because of the lower depth and width of penetration, but it takes longer processing time due to a lower material removal rate. The bigger grain size (smaller mesh size 100) results in lower surface improvement (higher R_a), because of the higher depth and width of penetration.

6.2.4 Effect of Abrasive Types

The aim of the experiment is to investigate the effects of abrasives types on the AFM process. DIN 1.2080 tool steel with 100 mesh size, Silicon carbide (SiC), aluminium oxide (Al_2O_3), and Garnet abrasives were used for this purpose.

The experiments were repeated for two specimens in each condition and the averages of five surface roughness measurements were taken perpendicular to the media flow directions.

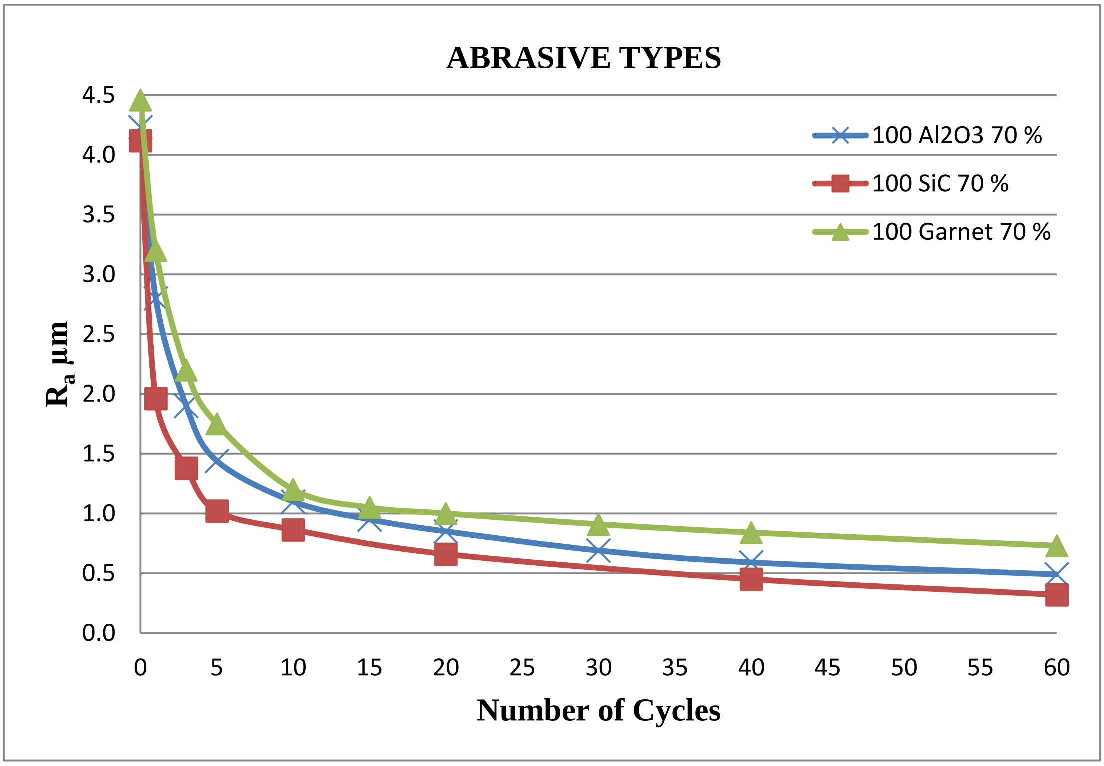


Figure 6.4 The effect of abrasive types

The Figure 6.4 shows the surface roughness value (R_a) for each abrasive type. The surface roughness value decreases with increase in number of cycles for all abrasives. The surface roughness of the WEDMed surfaces significantly changes in first 10 cycles for all abrasives. The trends are similar for all abrasive types, the final surface roughness values are different for each abrasive type. The abrasive media prepared by SiC abrasive gives better surface roughness according to the final results, followed by Al_2O_3 and Garnet based media.

6.2.5 Effect of Pre-machining Conditions (Rough and Finish cut)

In die and mould making industry, to achieve the required surface quality many rough and finish cuts are carried out during EDM machining. For example to obtain a 0.30 μm surface roughness (R_a) value, about five stages are suggested by famous WEDM machine manufacturers [88].

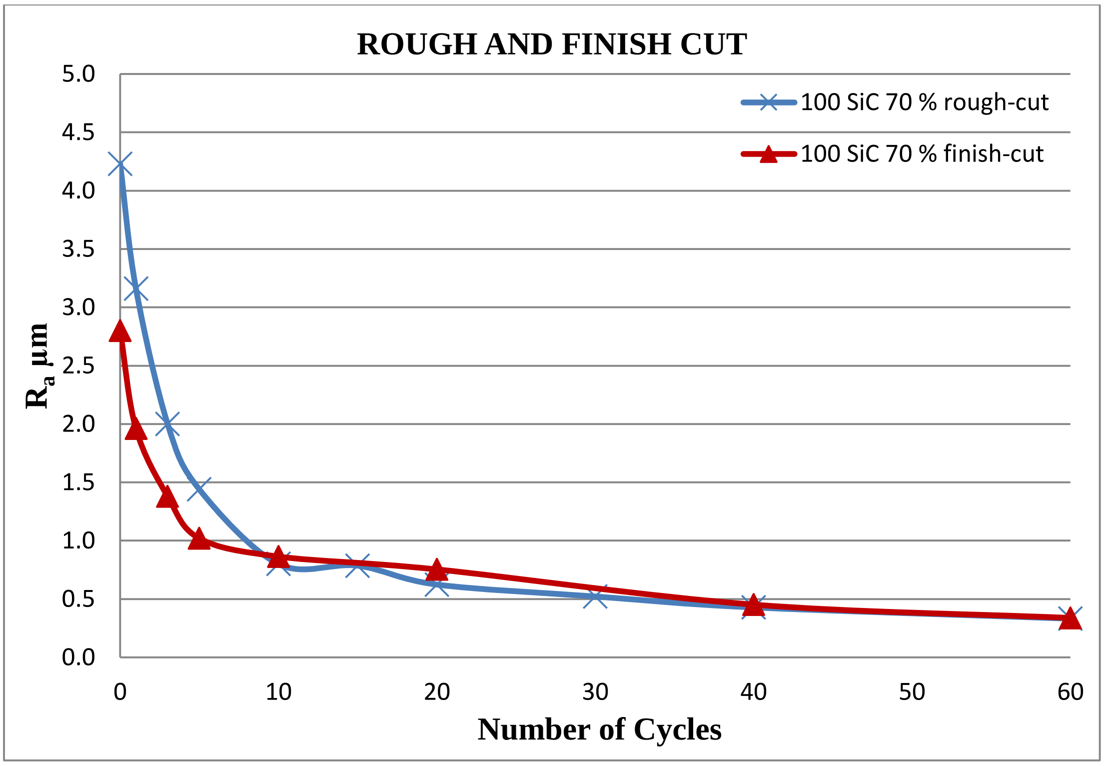


Figure 6.5 The effect of the wire cut conditions of wire EDM

The experimental study was performed on two types of specimens rough-cut (R_a = 4.5 μm) and finish-cut (R_a = 2.6 μm) by WEDM.

In the first 10 cycles of the machining, the surface roughness (R_a) value of the rough-cut workpiece reaches the surface roughness (R_a) value of the finish-one as shown in Figure 6.5. This is one of the significant advantages of AFM for the EDMed surfaces. The finish-cut in WEDM is performed subsequently after rough-cut, so the total time and cost of cutting is higher. The cutting time and cost may be reduced by using AFM for WEDMed surfaces, i.e. only rough cut may enough.

6.3 Experiment 2

Three groups of DIN 1.2379 cold-work tool steel (hardened to 31, 45 and 55 HRC) were cut by WEDM. The surface roughness was measured and SEM images were taken from the surfaces before and after AFM for various processing cycles. The improvement of the surfaces with respect to the hardness was examined.

6.3.1 Surface Roughness Measurements

The results of the selected roughness parameters (R_a, R_q, R_z) for three hardness groups are presented in Figure 6.6. The values are average of 18 measurements perpendicular to the flow directions. The surface roughness decreases with increase in number of operating cycles for all hardness values. The surface roughness of the WEDMed surfaces significantly changes in first 20 cycles and then settles to a saturated level gradually. The surface roughness after 50 cycles is decreased slightly. Although all trends are similar for all hardness groups, the final surface roughness values are different. The harder workpiece has a better surface roughness according to the final measures. This result will be explained together with the SEM images of the surfaces given in the following section. Noticed that this surface roughness values were obtained by using 180 mesh abrasives, better finishing may be obtained low abrasive sizes with subsequent operations.

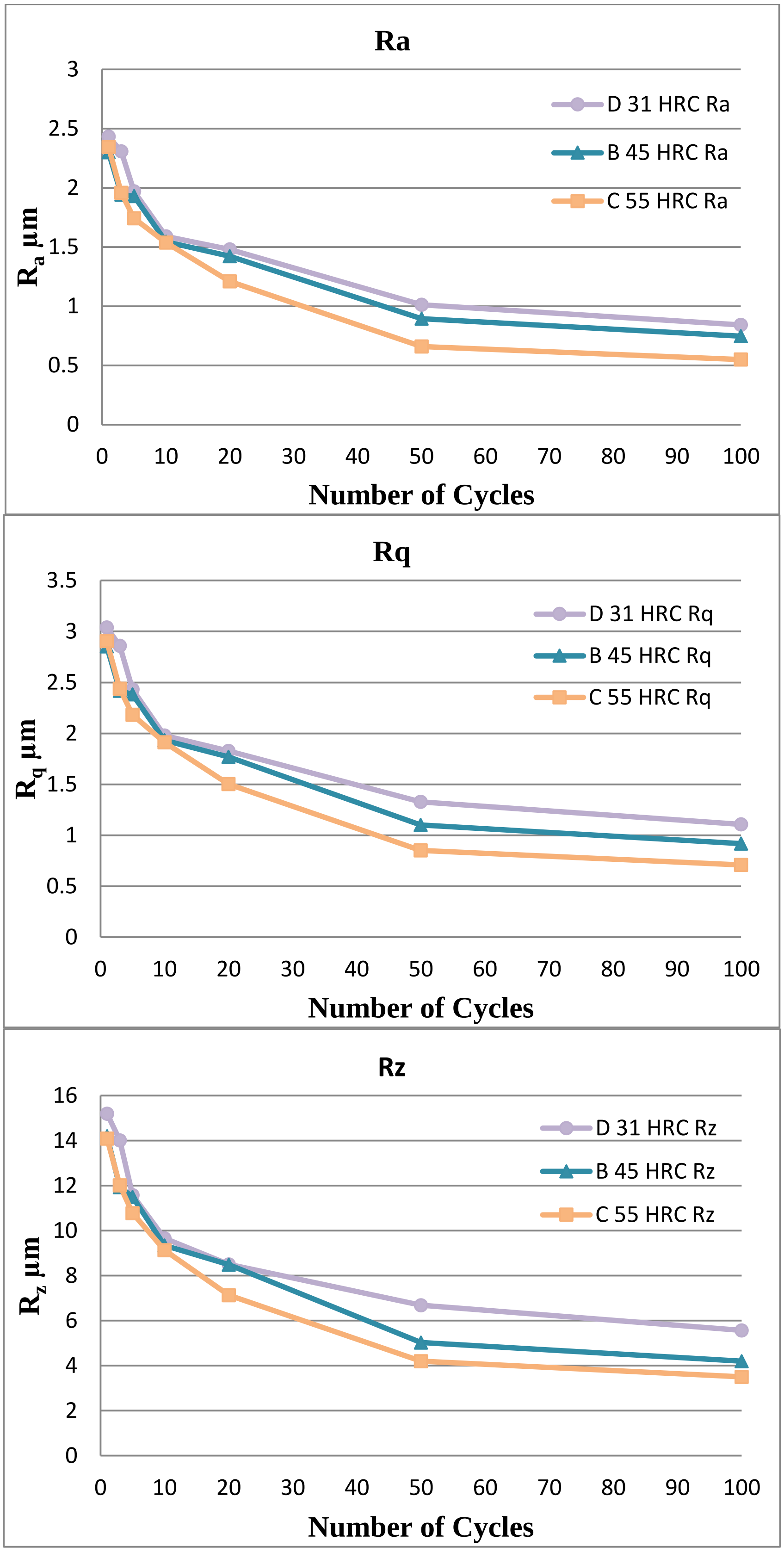


Figure 6.6 Variation of surface roughness versus AFM cycles

6.3.2 SEM Images

SEM images taken from the surfaces of the specimens are shown in Figure 6.7. During WEDM process, rapid heating and cooling occur and cause heat affected layer on the machined surface. This layer is generally formed by the sticking of the non-removed debris and also the depth of material affected from high temperature. The top of the layer consists of re-solidified layer and has a re-cast structure. The recast layer seems in white colour on microscope and thus it is commonly referred to as the white layer. The white layer is very hard and brittle and has micro cracks.

In Figure 6.8, microscopic photographs of the white layers for three groups of specimens are given. In the first 5 cycles of the AFM process, the white layer is removed for all specimens. This can be seen from Figure 6.7, as the improvement in the surface roughness values of all groups are similar up to 5 AFM cycles[3].

After removal of the white layer, abrasion behaviours of the three hardness groups were changed. In the softer specimens (31 HRC), indentation of the abrasive particles to the surfaces was observed. For harder group (55 HRC) smearing and plowing were less and the final surface roughness is better. The differences between the initial and final surfaces of the three groups of specimens can be seen in Figure 6.9.

6.4 Experiment 3

The aim of the experiment is to investigate the effects of abrasives types on the AFM process. Silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C), and Garnet abrasives were used for this purpose. The surface improvement and material removal (MR) was considered as performance parameters. Workpiece material was chosen with different hardness (15 and 55 HRC) of DIN 1.2379 tool steel, the two-way AF machine was used.

6.4.1 Surface Roughness Measurements

The experiments were repeated for three specimens in each condition and the averages of five surface roughness measurements perpendicular to the media flow directions were taken. Figure 6.10 and Figure 6.11 show the surface roughness value (R_a) for each abrasive type. The surface roughness value decreases with increase in number of cycles for all abrasive and workpiece types.

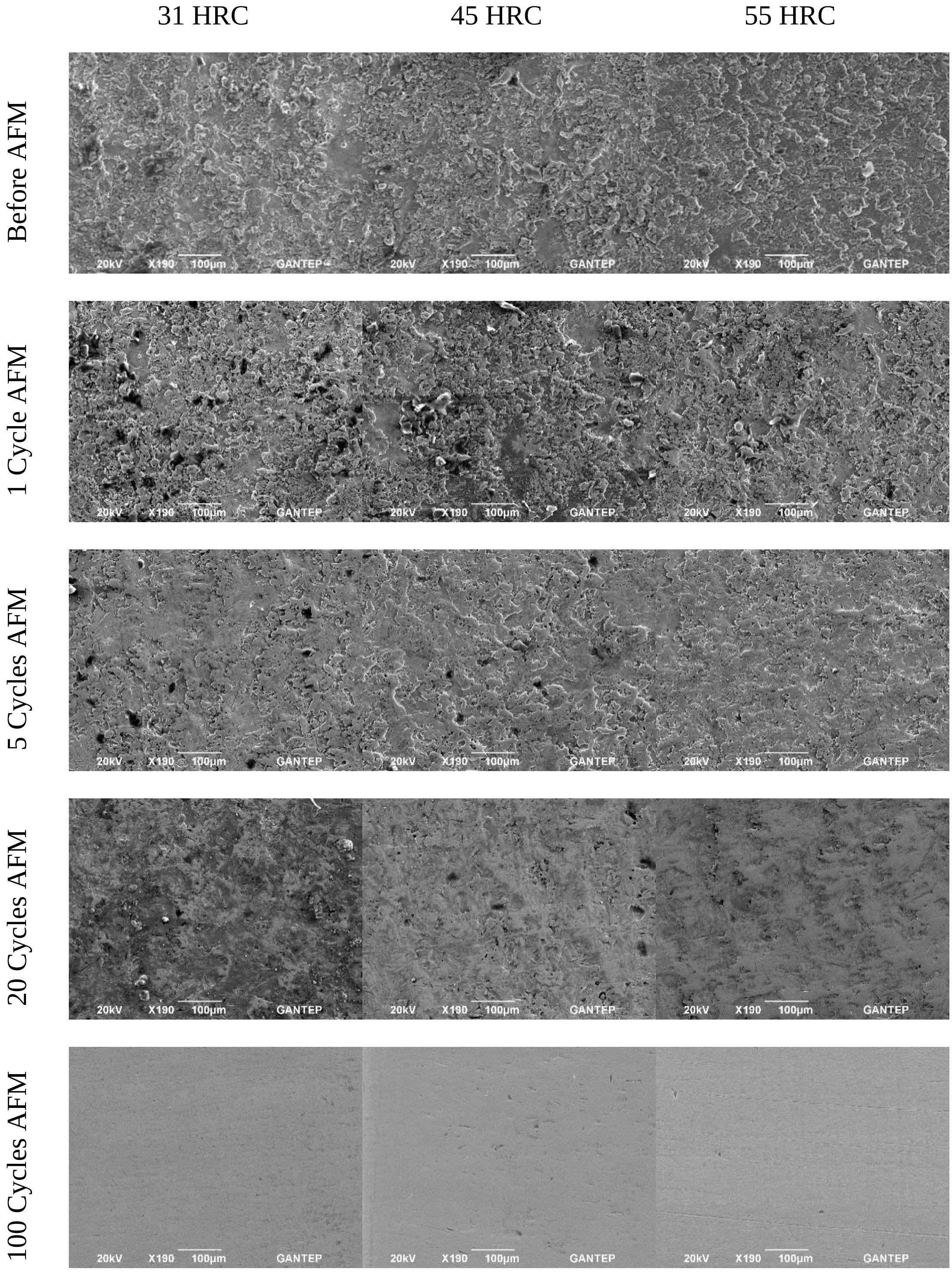


Figure 6.7 SEM images of AFM (x 190)

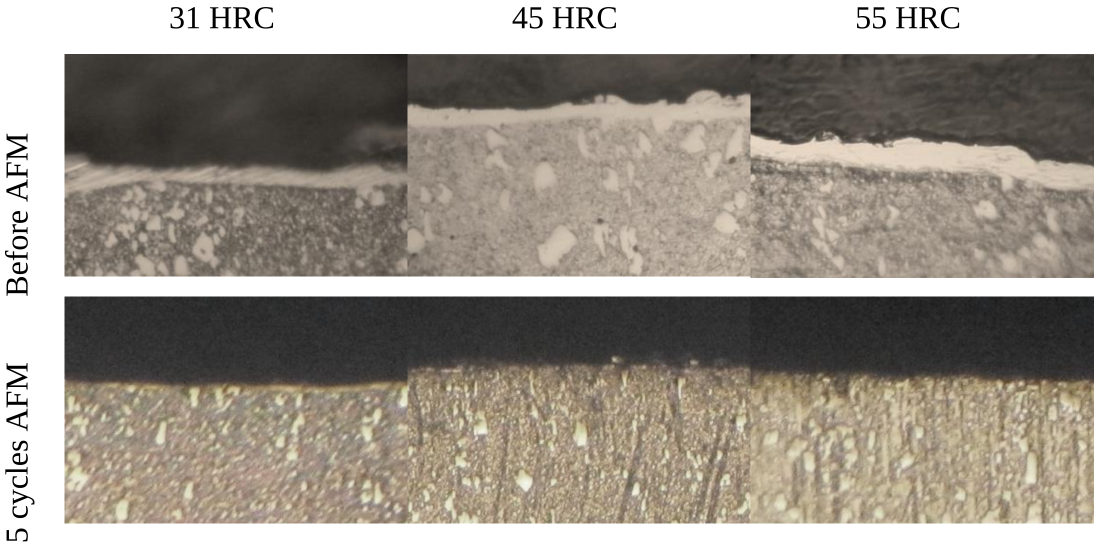


Figure 6.8 Microscopic photographs before and after AFM process

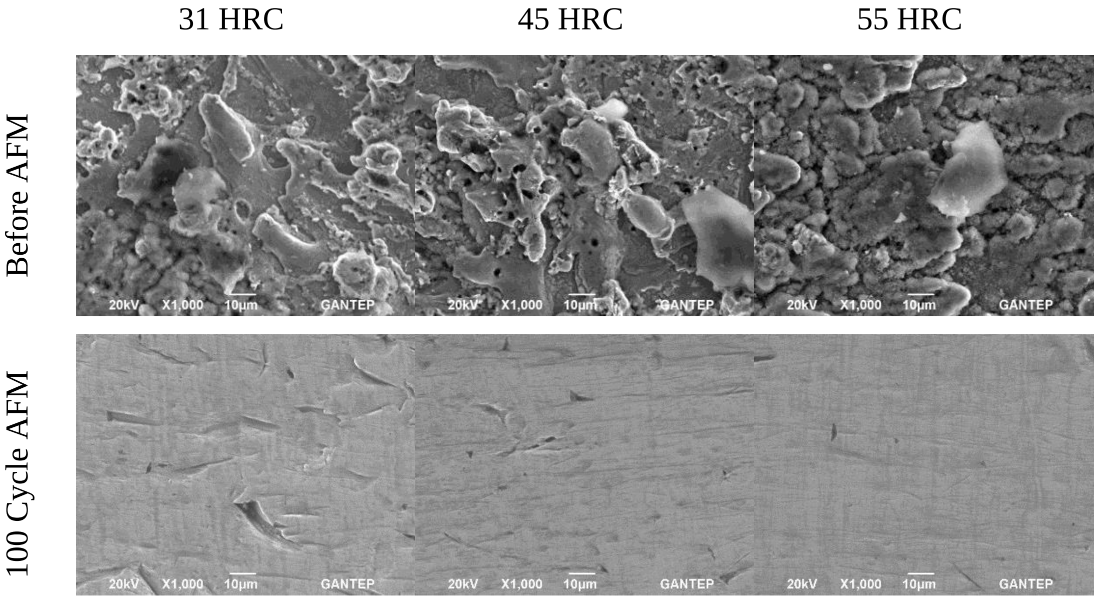


Figure 6.9 SEM images of AFM (x 1000)

The surface roughness of the WEDMed surfaces significantly changed in first 3 cycles for hard workpiece, in 10 cycles for soft one and then settles to a saturated level gradually. The surface roughness after 10 cycles for hard and 20 cycles for soft workpiece is decreased slightly. Although all trends are similar for all abrasive and workpiece types, the final surface roughness values are slightly different for each workpiece type. The abrasive media prepared by B_4C abrasive gives better surface roughness according to the final results, followed by SiC, Al_2O_3 and Garnet based media. The final surface roughness values of harder and softer workpiece with respect to the types of abrasives are given in Table 6.1.

Table 6.1. Final surface roughness of different workpieces

	B_4C Ra (µm)	SiC Ra (µm)	Al_2O_3 Ra (µm)	Garnet Ra (µm)
15 HRC	0.11	0.14	0.24	0.32
55 HRC	0.066	0.091	0.110	0.152

The improvement in surface profile is evident (Figure 6.12). The measurements were obtained by Mitutoyo SJ 401 surface roughness measuring machine before and after AFM process that was machined by SiC based abrasive media.

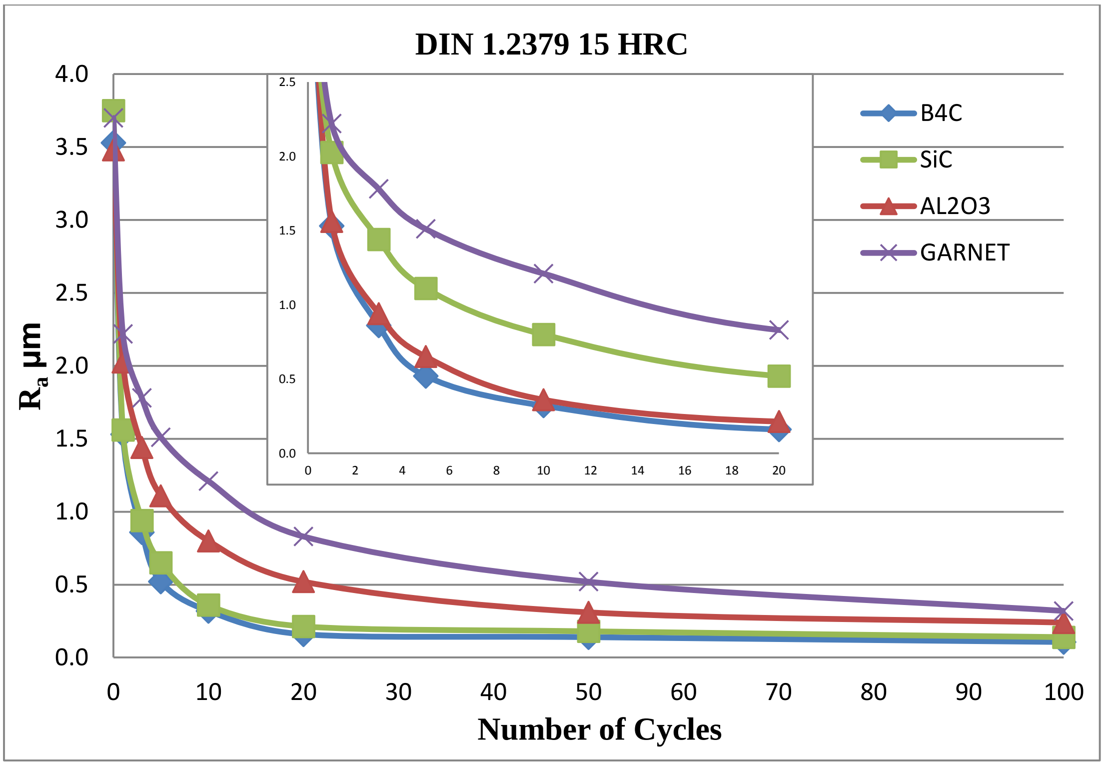


Figure 6.10 Change in the surface roughness for 15 HRC workpiece

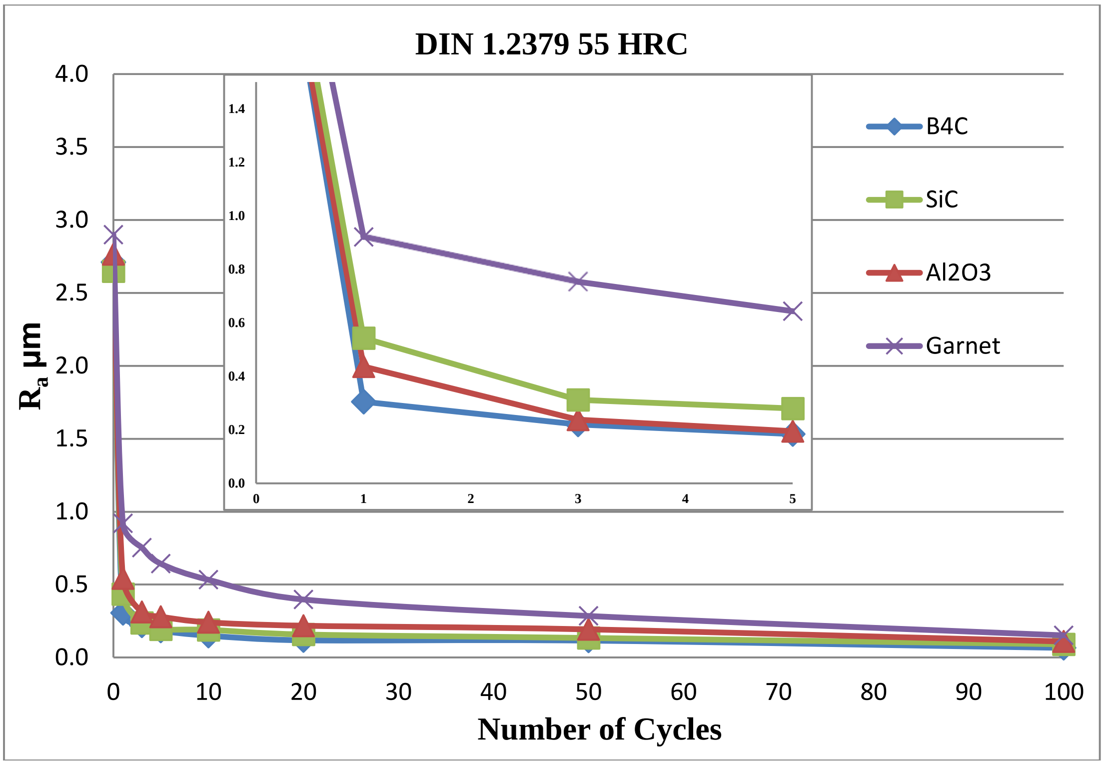
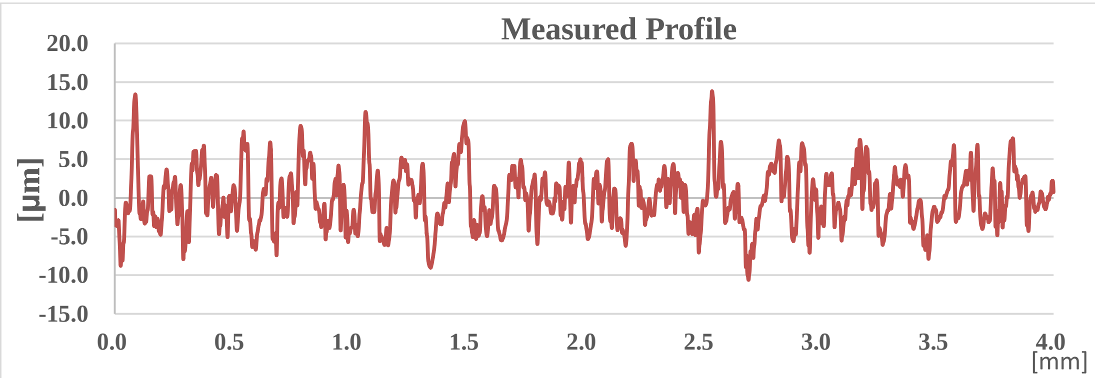


Figure 6.11 Change in the surface roughness for 55 HRC workpiece



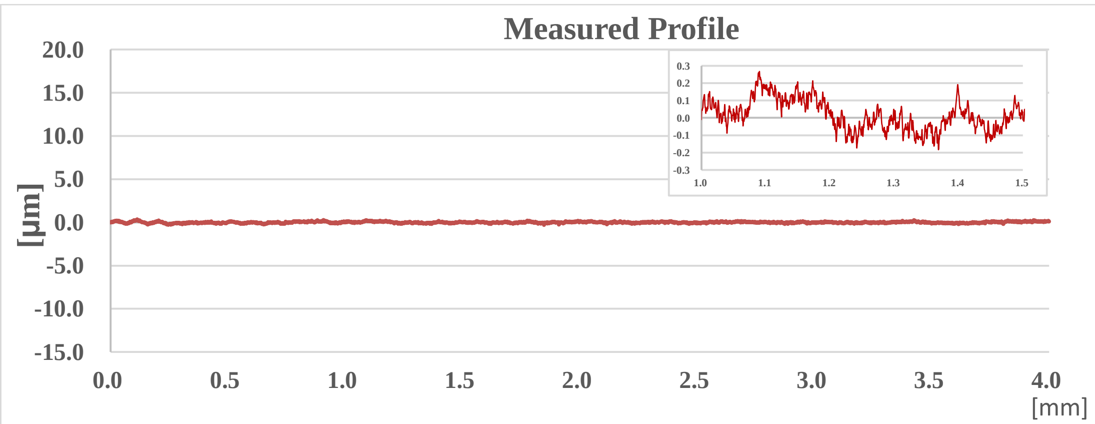


Figure 6.12 Surface profile before and after AFM (SiC abrasive 55 HRC workpiece)

6.4.2 Material Removal

Figure 6.13 and Figure 6.14 show that the material removal (MR) increases nonlinearly with increase in the number of cycles. The rate of MR decreases with number of cycles. This is confirmed by literature [10]. The reason for the slight decrease in material removal rate can be explained as a result of asperities on the workpiece surface before AFM. When the abrasive particles within the media machine the peaks, they become flatter than before and in the following cycles, the material removal is decreased. The trend of material removal for all abrasive types is similar, but the total material removal is lower for of garnet based media.

6.4.3 SEM Images

The EDMed surface is unlike that produced by any traditional machining process; it is characterized by globules and random debris of re-deposited and recast material. This re-cast surface is generally named as white layer due to its appearance in micro graphs. The white layer is harder than the original workpiece material and contains micro cracks. So that, it is required to remove this layer during finishing [84]. The SEM images of the surfaces finished by the different abrasive types, are given in Figure 6.15. The globules and debris were completely removed in first cycle for B_4C and SiC based abrasive media, however, five and twenty cycles were required to completely remove the globules and debris for Al_2O_3 and Garnet, respectively.

Sectional microscopic views of the white layers for four groups of specimens are given in Figure 6.16. After removal of the white layer, abrasion behaviours of the four groups were changed. In the specimens finished by B_4C and SiC based media have less smearing and ploughing, no indentations of the abrasive particles to the surfaces were observed and the final surface roughness are better.

For Al_2O_3 based media finished specimen, the globules were fully removed from the surface in the fifth cycle but the lay of craters was fully removed after the twentieth cycle and also has less ploughing. For the specimen finished by Garnet based media, the globules were fully removed in the fifth cycle, but the debris was fully removed after the fiftieth cycle. The SEM images and sectional microscopic views are in well agreement with the surface roughness measurements given in Figure 6.10 and Figure 6.11.

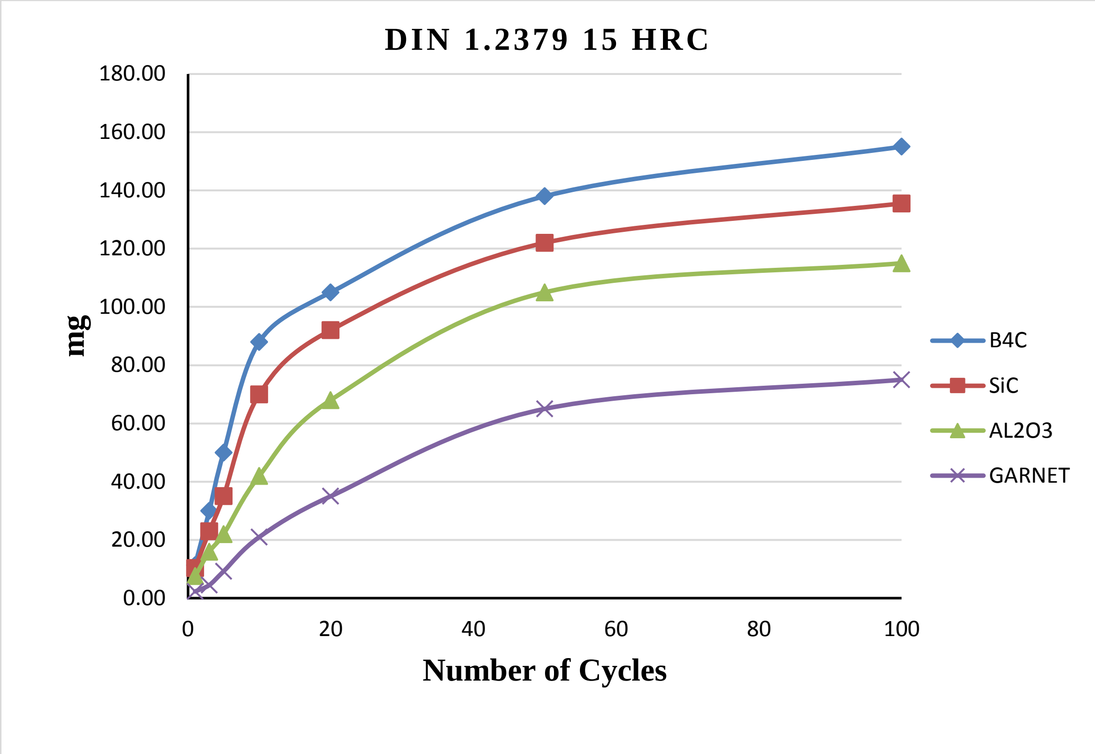


Figure 6.13 Variation of material removal versus AFM cycles

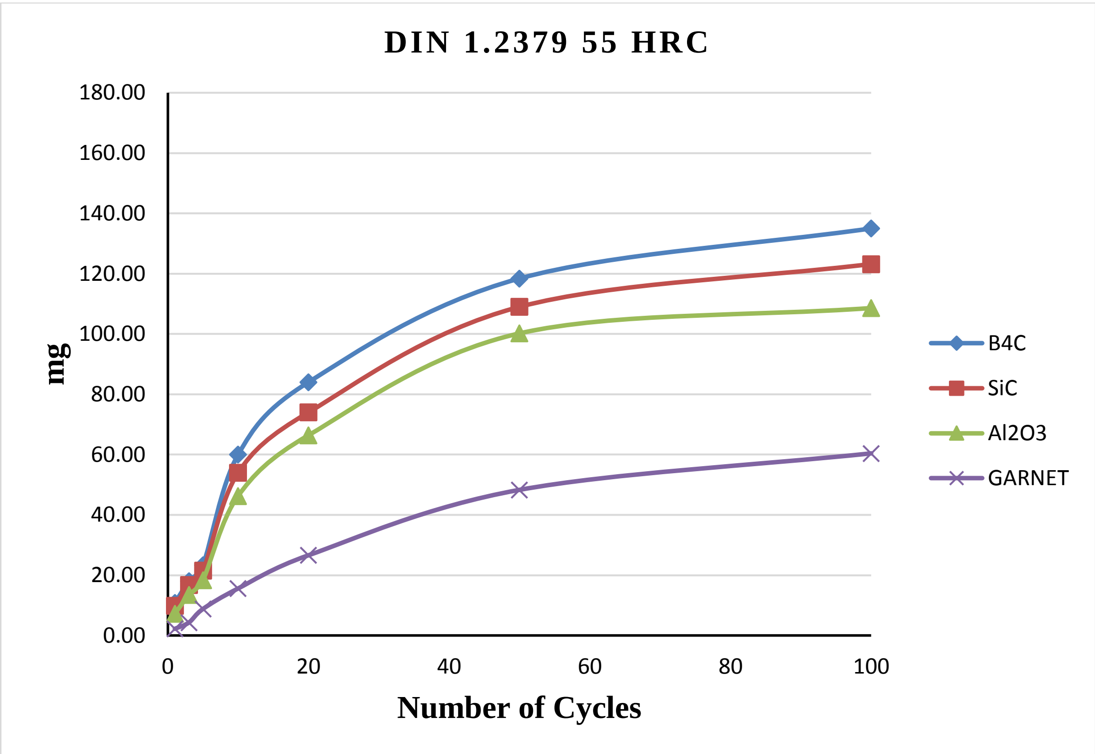


Figure 6.14 Variation material removal versus AFM cycles

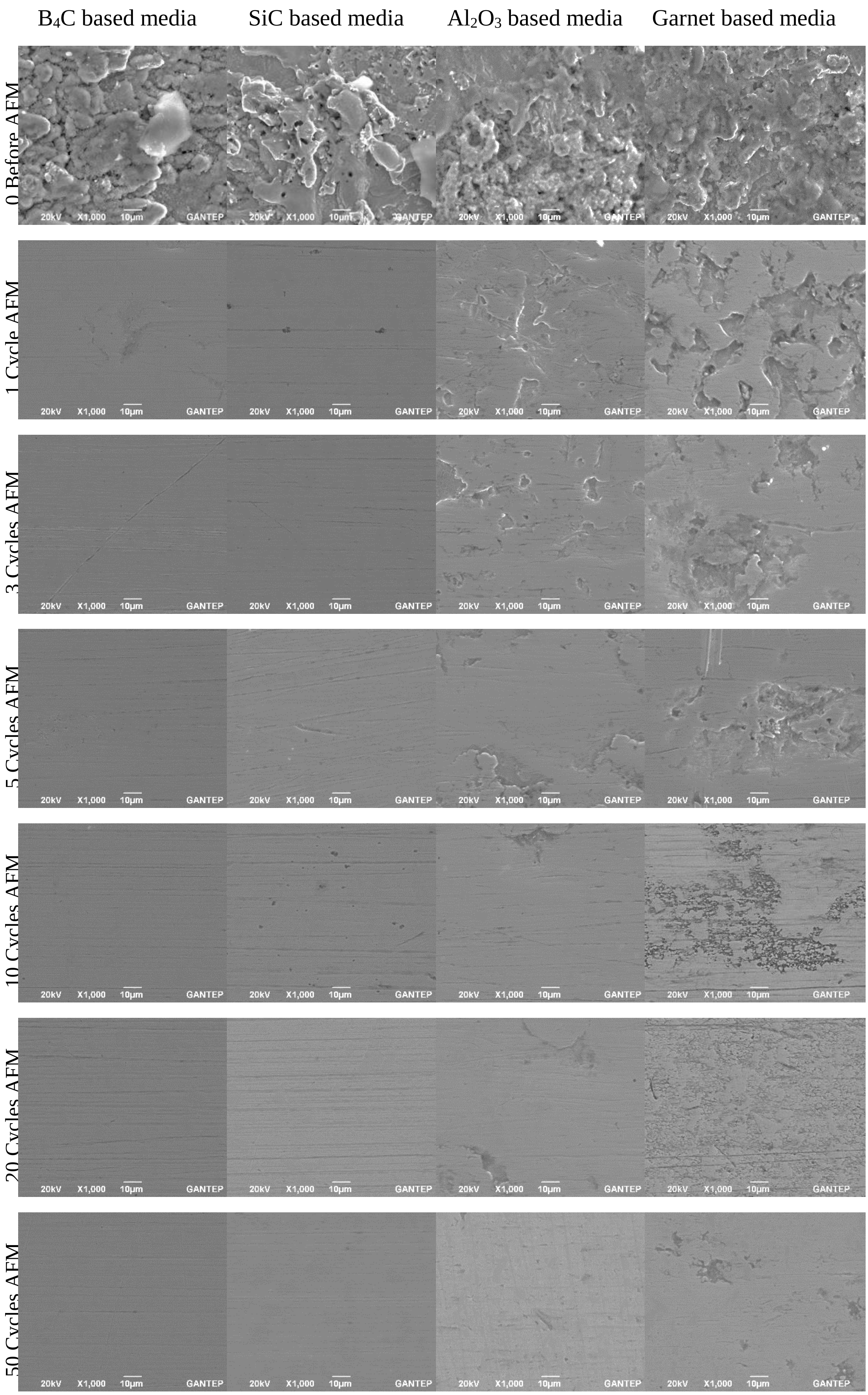


Figure 6.15 SEM images of DIN 1.2379 55 HRC specimens (x 1000)

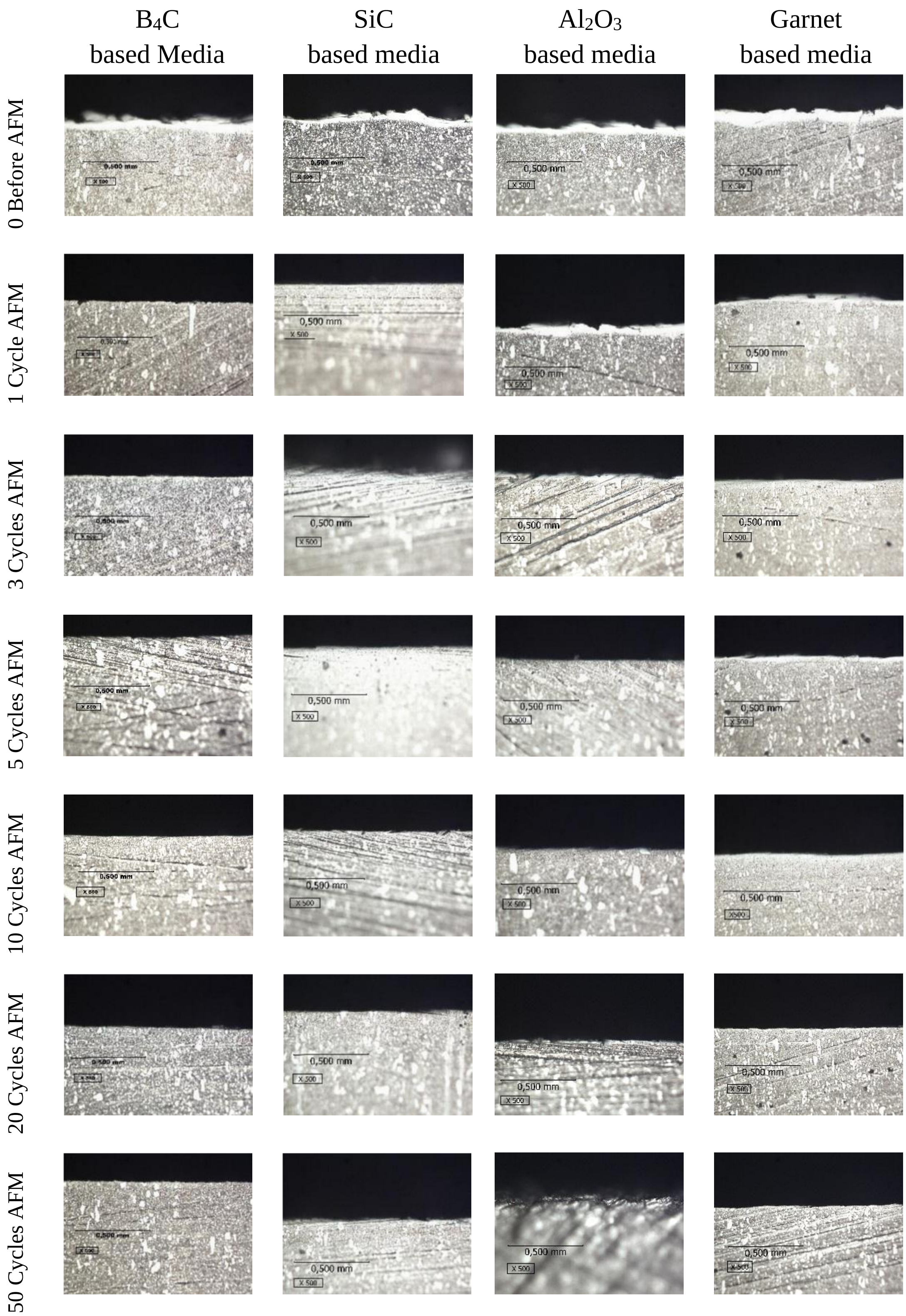


Figure 6.16. WLT views of B_4C, SiC, Al_2O_3 and Garnet based media for various number of cycles

6.4.4 White Layers

Figure 6.16 shows the variation of the removal of white layer versus the number of AFM cycles for DIN 1.2379 55 HRC specimens. The results of SEM images and the sectional microscopic views are in good agreement. The white layers were fully removed in the first cycle of B_4C and SiC based media. In the case of Al_2O_3 and Garnet based media, five and twenty cycles were required to fully remove the white layers.

6.5 Experiment 4

The purpose of this experiment is to investigate the effects of AFM parameters on WEDMed Titanium (Grade 1) surfaces. The one-way AF machine was used for this experimental study.

6.5.1 Effect of Number of Cycles

The effect of number of cycles on surface roughness value (R_a) was shown in Figure 6.17. The R_a value improve in the first machining cycles because of the existence of peaks in early stages of machining, but as these peaks get machined the improvement in surface roughness (R_a) values slowly decreases. After 60 cycles the surface roughness (R_a) value reaches about 1.6 μm, which shows that the AFM of titanium is difficult then 1.2379 tool steel.

6.5.2 Effects of Abrasive Mesh Size

The experimental study performed by using 100, 180 and 240 mesh sizes to examine the effect of the mesh sizes on the surface roughness in AFM process for Titanium workpiece. Figure 6.18 shows the effects of abrasive mesh sizes on surface roughness. The surface roughness gets better in the first cycles for the bigger grain sizes due to the higher material removal. As the number of cycles increases the surface roughness values gradually reach certain levels. The final roughness values are 1.22, 1.1 and 1.0 μm for 100, 180, 240 mesh sizes, respectively.

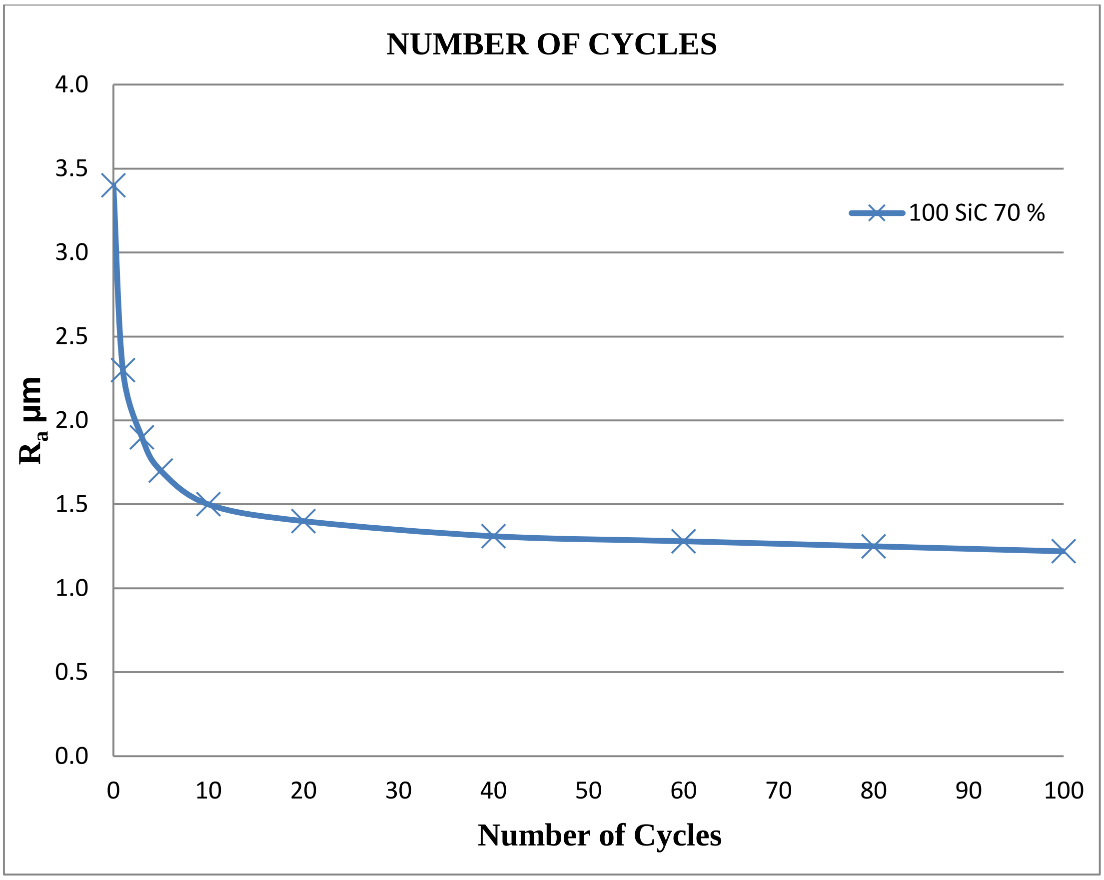


Figure 6.17 Effects of number of cycles on surface roughness R_a

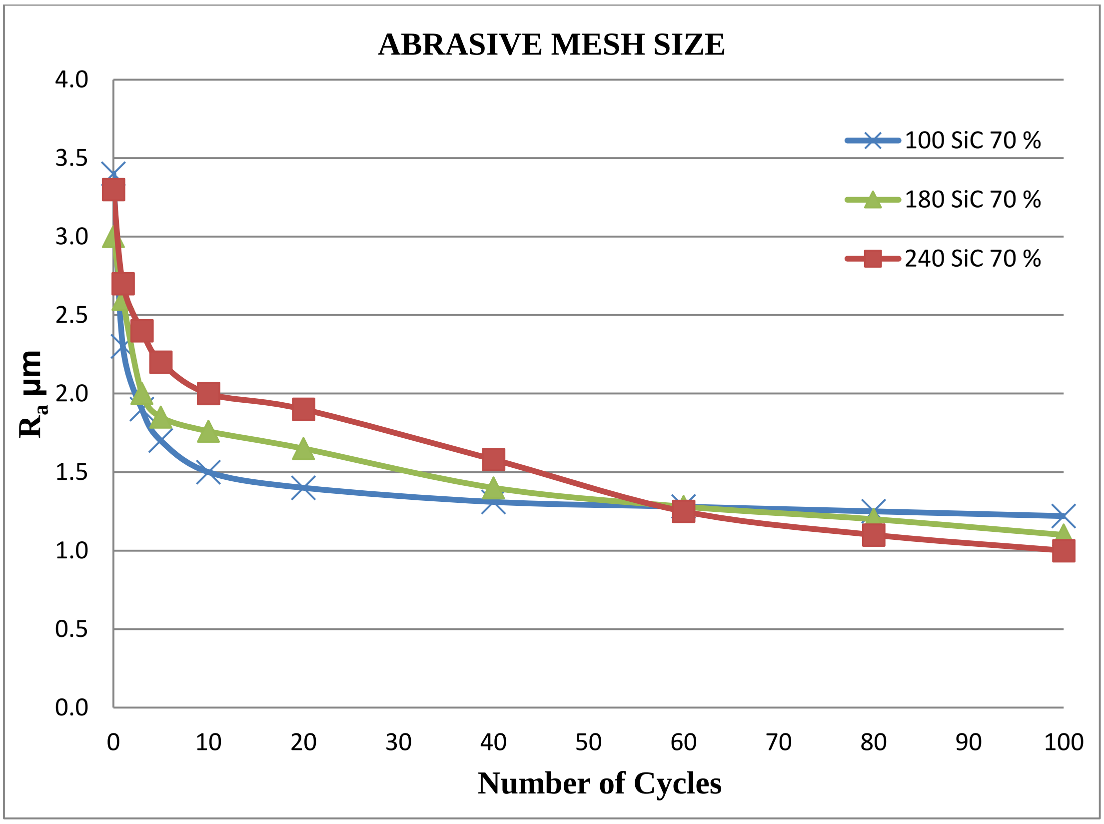


Figure 6.18 Effect of abrasive mesh sizes on surface roughness R_a

6.5.3 Effects of Abrasive Concentration

Two different media concentrations (40% and 70%) were chosen based on the preliminary experiments. Figure 6.19 shows that increasing the abrasive concentration decreases the surface roughness (R_a) value. The reason is that as the abrasive concentration increases, the number of grains in contact with the workpiece surface increases; resulting in more abrasion and change in surface roughness.

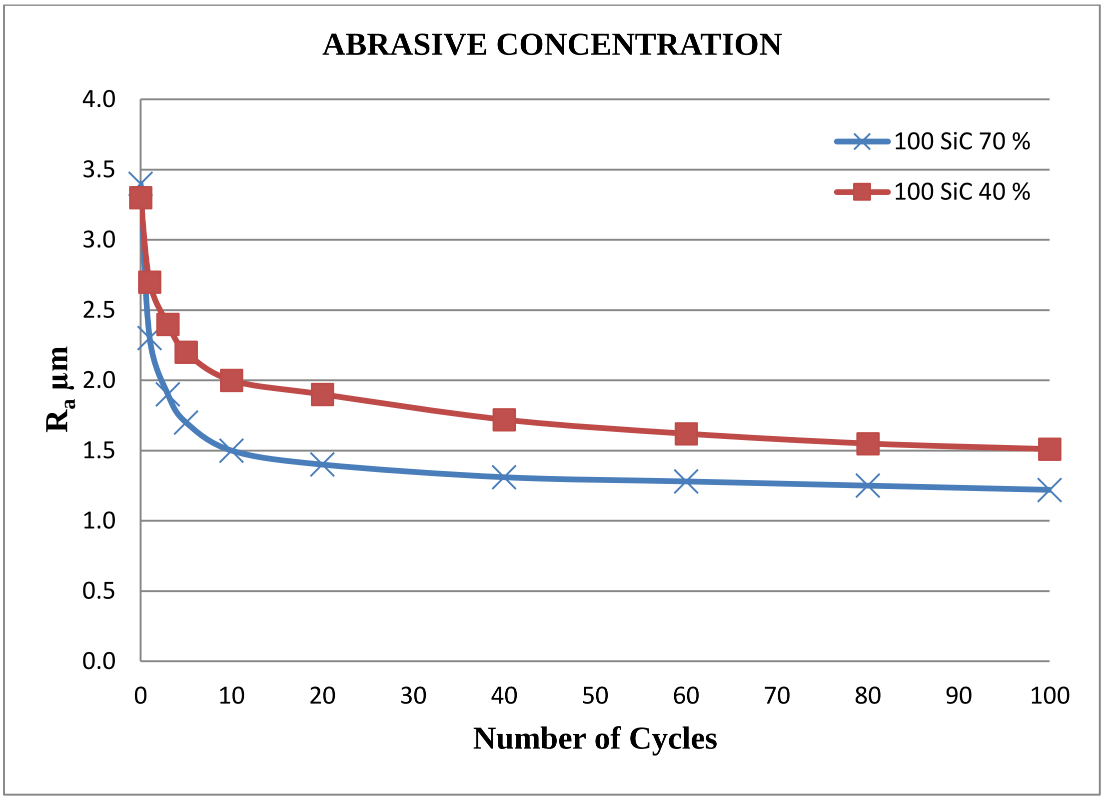


Figure 6.19 Effect of abrasive concentration on surface roughness R_a

CHAPTER 7

CONCLUSIONS AND FUTURE WORKS

7.1 Introduction

In this thesis, the effects of the AFM parameters on WEDMed surfaces were studied and the following conclusions have been drawn from the four sets of experimental studies.

7.2 Experiment 1

- As the number of cycles increases the surface roughness (R_a) decreases. In the first few cycles the improvement in R_a value is better because of the existence of peaks in early stages of machining, but as these peaks get machined the percentage improvement in R_a slowly decreases.
- With the increase in abrasive concentration, the surface roughness (R_a) decreases. The surface roughness (R_a) decreases with increasing abrasive concentration and mesh size (smaller grain size). The depth and width of the penetration are depending on the grain size and bigger grain size thus, more material removal happens with a lower surface quality (higher R_a values). Therefore, a proper abrasive size must be determined when the machining time and surface roughness are both functional requirements in AFM.
- In the first 10 cycles, the surface roughness values of the rough-cut specimens reach the finish-cut ones. The pre-machining time and cost may be reduced by using AFM for rough WEDMed surfaces, i.e. only rough cut may enough.

7.3 Experiment 2

The effect of workpiece hardness of WEDMed DIN 1.2379 tool steel on abrasive flow machining was investigated. From the experimental results, the following conclusions have been derived:

- The white layer formed during WEDM is successfully removed by AFM in a few cycles. The removal of white layer eliminates surface cracks and so the fatigue strength may be improved.
- The surface quality is improved by AFM for all hardness groups. The surface roughness of the WEDMed surfaces significantly changes in the first 20 cycles and then settles to a saturated level gradually. The surface roughness after 50 cycles is decreased slightly.
- Although the trends of surface roughness measurements are similar for all hardness groups, the results show that harder material has more surface improvement than the softer ones.

7.4 Experiment 3

The effect of abrasive types (SiC, Al_2O_3, B_4C and Garnet) on abrasive flow machining was investigated for WEDMed DIN 1.2379 cold-work tool steel. The experimental results, yield to the following conclusions:

- The white layer formed during WEDM is successfully removed by using all types of abrasives.
- The results of SEM images and the sectional microscopic views are in well agreement. The white layers were fully removed in the first cycle of B_4C and SiC based media. In the case of Al_2O_3 and Garnet based media, five and twenty cycles were required to remove fully the white layers.
- Although the trends of surface roughness measurements are similar for all media groups, the media prepared by B_4C and SiC have more surface improvement than Al_2O_3 and Garnet.
- Since both B_4C and SiC exhibit similar surface improvements, SiC can be preferred due to its lower cost.

7.5 Experiment 4

The effects of AFM process parameters such as the number of cycle, the abrasive mesh size and concentration on titanium (Grade 1) were examined. The experimental results show that the surface roughness (R_a) value decreases with increasing number of cycles. The percentage improvement of the titanium (Grade 1) is less compared to those of 1.2379 tool steel.

7.6 General Conclusions

Based on the experimental the conclusions are made:

- AFM can be successfully applied to the WEDMed surfaces for improving the surface quality. The resulting surface roughness values are similar to the surface quality those obtained from lapping and super-finishing processes.
- The number of cycle is one of the significant parameters which affect the AFM performance. As a general rule, the surface roughness (R_a) value decreases with increasing number of cycles. In the first few cycles, the improvement in R_a value is high because of existence of peaks in early stages of machining, but as these peaks get machined the percentage improvement in R_a values decreases slowly, then it settles to a saturated level gradually.
- The second significant AFM process parameter is the abrasive grain size which determines the depth of finishing, so as the material removal and the final surface roughness. The finer grain size (larger mesh size) results in better surface improvement (lower R_a) because of the lower depth and width of penetration, but it takes longer processing time due to the lower material removal rate. The bigger grain size (smaller mesh size) results in higher material removal rate and worse surface improvement (higher R_a), because of more depth and width penetration.
- The third significant AFM process parameter is the abrasive concentration. With increasing in abrasive concentration in abrasive media, the surface improvement increases. The reason is that as the percentage concentration increases, the number of the active grains in contact with the workpiece surface increases. From the experiments the optimum abrasive concentration is determined as 70 % in weight.
- In die and mould manufacturing industry, the dies and moulds are manufactured from the hardened tool steel by using WEDM process. These parts must

be cleaned and polished before put them into service. The experimental results showed that the harder workpiece has better surface improvement in AFM process.

- In the first few cycles, the surface roughness values of the rough-cut specimens reach the finish-cut ones. The pre-machining time and cost may be reduced by using AFM for rough WEDMed surfaces, i.e. only rough cut may enough.

- During EDM process, the rapid heating and cooling occur and they cause recast layers that are generally formed by the sticking of the non-removed debris on the surface seems white colour on microscope and thus it is commonly referred to as the white layer. The white layer is very hard and brittle and has micro cracks. The white layer formed during WEDM is removed successfully by AFM in a few cycles. The removal of white layer eliminates surface cracks and improvement of the mechanical properties on the workpiece surface for example the fatigue strength may be improved.

- All media types prepared by SiC, Al_2O_3, B_4C and garnet abrasives remove successfully the white layers and improve the surface quality. The material removal and the hardness of abrasives are related directly.

- The influence of the AFM process parameters on the surface roughness of pure titanium (Grade 1) are similar to the tool steel, but the improvement of the surface quality is better for the tool steel.

7.7 Future Works

The following may be recommended for the future studies on this areas:

1. The effects of AFM parameters on the “hard to machine” materials, such as Ti-6Al-4V and Inconel need to be investigated.
2. The influence of AFM parameters for complex workpiece geometries can be studied.
3. The sub-surface behaviour, especially the residual stress distribution of the AF machined surfaces may need to be exposed.
4. The economic gains and the effective life of the abrasive media for different workpiece/media combinations may be studied.

5. The rheological properties of the AFM media, with and without the abrasive grains, must be identified. A proper modelling and simulation of the fluid flow during AFM process may be developed.
6. The subsequent relationship between the rheological and finishing parameters may be investigate. It is proposed that this could be achieved if the relevant data affecting to the viscosity calculations are made at the end of each cycle.

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PUBLICATIONS

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