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A Review of Cylindrical Grinding Process parameters by using various Optimization techniques and their effects on the surface Integrity, Wear Rate and MRR.

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Abstract —*Grinding is the material removal and a surface finish process in which the material is removed from the work surface in the phase of small chips by process of tiny abrasive particles of grinding wheel. Surface finishing process is generally the last operation performed to obtain the higher surface finish and to maintain closer tolerances. Components having a high surface finish and close tolerances are one of the most essential requirements in recently developed industries. This paper presents a literature collection on the experimental study and use of different optimization techniques on cylindrical grinding process parameters to measure the effects on Surface Integrity, wear rate and Material Removal rate.*

Keywords*-Grinding; Cylindrical Grinding; Process parameters; Optimization; Performance parameters; Research Trends*

I. INTRODUCTION

1.1. Surface Finishing Process

The various machining operations are performed on the workpiece material to produce the required shape and size of the product with high surface finish & close tolerance by removal of excess material from blank in the form of chips. [41] When the workpiece is subjected to different manufacturing operations, intense mechanical stresses and localized heating get involved in the process, thus create machining marks on the surface of the workpiece. In combination with the machine, the workpiece and tool on which they mounted to create a vibratory system responsible for random, forced or induced vibration. Because of the vibrations, the machined component surfaces get damaged in terms of surface finish and surface integrity. The degree of surface finish describes the geometry and micro structural quality of the machined surface. [41] The different methods used for finishing the surfaces of the parts are discussed below:

- Grinding
- Lapping
- Honing
- Buffing
- Barrel Rolling
- Polishing
- Super finishing
- Burnishing

Table 1.1 Various surface finish methods and their finishing ranges [44]

Process	Average applications (µm)
Grinding	0.1 - 1.6
Lapping	0.05 - 0.4
Honing	0.1 - 0.8
Buffing	0.05 - 0.5
Super finishing	0.05 - 0.2
Burnishing	0.2 - 0.8

II. GRINDING PROCESS

Grinding is generally known as the Abrasive machining. Abrasive machining is the surface finish and material removal process from the workpiece surface in the form of minute particles. The removal of material takes place by the process of a typical shaped abradant particle. Abrasive particles are used in bonds wheel, coated belts or simply loose particles. [41]

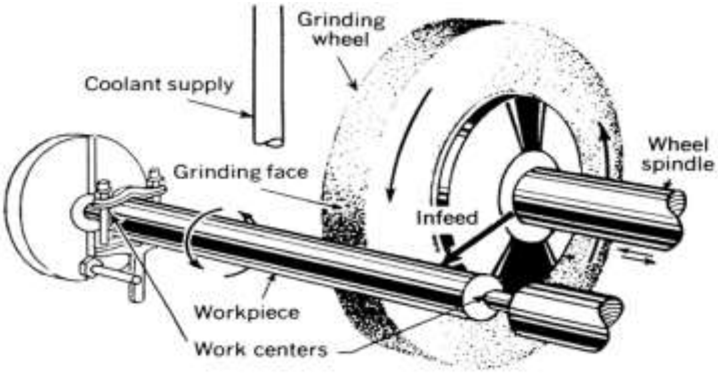


Figure.1.1 Grinding Process [41]

A grinding machine, generally abbreviated to the grinder (surface or cylindrical), is any of power apparatuses utilized for surface finishing. Rough wheel is employed for grinding as the ‘cutting tool’. Each grain on the outer surface of wheel cuts a little chip from the workpiece by shear distortion.

2.1. Grinding Mechanism

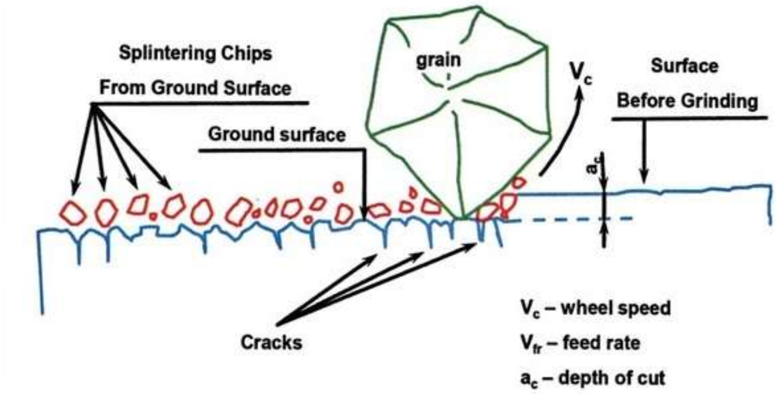


Figure 1.2 Basic Mechanism of Grinding Process [41]

2.2. Role of Cylindrical Grinding

Nevertheless, in the recent years, consideration has been compensated to operations, which enhance the surface characteristics, by plastic deformation. Such performances are cited as plastic surface distortion. Surface Grinding comes under this classification and is ending up more broadly utilized. Abrasive, grinding wheel is utilized to move over the surface of the work material. [44]

In the course of conventional machining process some geometric error like, out of roundness and cylindrical inaccuracies surface defects such as roughness, micro cracks, waviness surface burning, residual tensile stresses and plastic creep which make the component unfit for precision applications. Less surface finished material leads-at the break of oil films on the crests of micro irregularities that result in excessive wear and friction of the surface in contact. Some functional and tribological properties like fatigue strength, corrosion, wear resistance and friction are dependent on surface finish and surface texture. [43]

To minimize the above listed imperfections, cylindrical or surface grinding process is used to smooth the surface by decreasing the peak to valley height. Its other use is that it decreases the residual tensile stresses and macro irregularities by filling up cracks. Further, it hardens the surface and toughens the skin to make it more wear resistant.

III. TYPES OF GRINDING

The four most commonly used industrial Abrasion operations are:

- Cylindrical grinding
- Internal grinding
- Center less grinding
- Surface grinding [44]

3.1. Cylindrical Grinding

In cylindrical grinding, the workpiece revolves around a fixated rigid point and the machined surfaces are concentric to the revolution. The surfaces produced after cylindrical grinding might be straight, tapered, or contoured. There are four movements involved in this type of machine:-

1) The work piece must rotate.
2) The Abrasive wheel must revolve.
3) The work piece must pass the wheel.
4) The grinding wheel must pass the work.

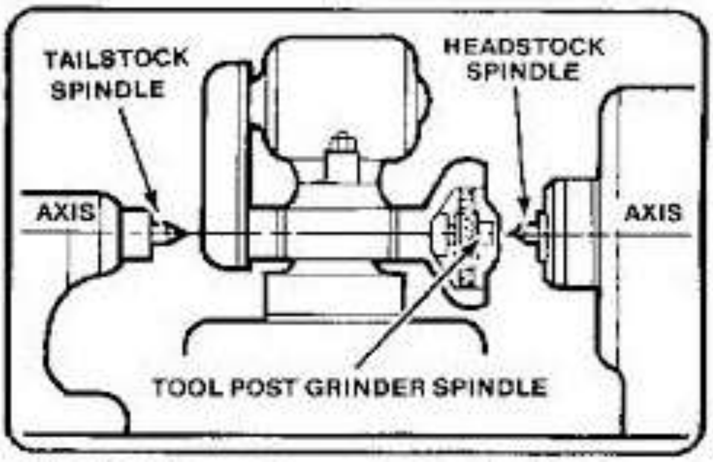


Fig1.3 Block diagram of outside Diameter Cylindrical Grinding [44]

Cylindrical grinding machines are also used for grinding contoured- cylinder, tapers, faces and shoulders, fillets, and even cams and crankshaft.

3.2. Internal Grinding

Internal grinders are used to produce internal surface within an already performed machining operation (i.e. Drilling, reaming, or bored hole) with the help of small abrasive grinding wheels at higher revolutions (RPM). The main components of an Internal grinding machine are the work head and wheel head. Internal grinding machines are classified according to the method of holding work, i.e. between center or centreless and method of operation i.e. normal or automatic. Internal grinding is not expensive and provides a high degree of surface finish.

3.3. Centerless Grinding

In Centerless grinding, work material revolves between an abrasive wheel and a governing drive wheel. The work material moves in a transverse direction and the grinding wheel remains fixed in internal centerless grinding. The softer grinding wheel employed for this because the area of contact between the grinding wheel and work material is relatively great. The two fundamental methods of Centerless grinding are "thru-feed" and "infield".

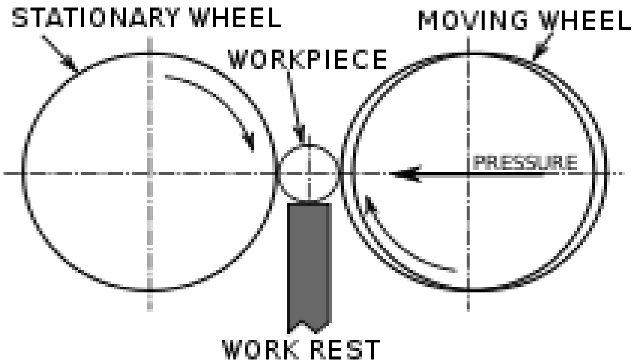


Fig.1.4 A Schematic of the Centerless grinding process [43]

3.4. Surface Grinding

Surface grinding process is commonly employed to produce flat, angular, or contoured surfaces. The work material is fed through a horizontal plane and against a revolving abrasive wheel. In this process, work material is either magnetically seized to the work table or may be machined by traversing or revolving motion of the work table. Horizontal spindle is used in most surface grinding machines which controls and allows upward and downward permitting either the edge or the face of the wheel to contact the work. [4]

IV. ABRASIVE WHEEL (SHAPE AND SIZE SPECIFICATIOS)

Abrasive wheels are used in all the forms, but the disc shape is most common. Disc wheel has a central hole for mounting and edges are used for grinding. For grinding piston rods and gear teeth, rod grinding wheel and taper wheels are used. [36]

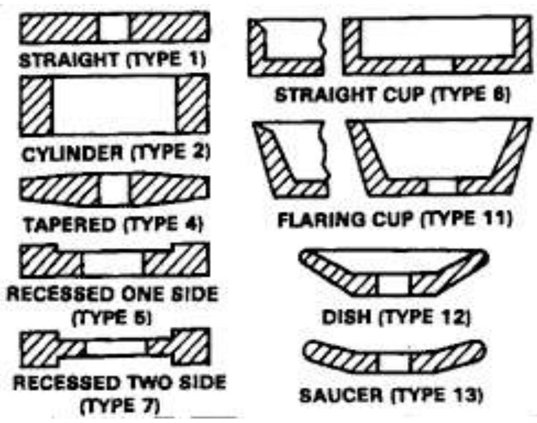


Figure 1.5 Different Types of Grinding Wheels [41]

4.1. Grinding Wheel's coding

The Indian Standard Coding system specializes the grinding wheel, according to the hardness, structure, bond and grain size of any wheel as compared to another. Specification of an Abrasive wheel is identified below;

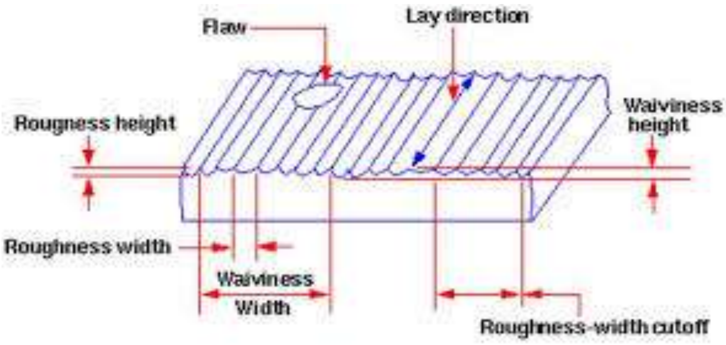
- W: Abrasive Type (Manufacturer's)
- C: Abrasive Name
- 30: Grit size
- L: Grade
- 5: Type of Structure
- R: Type of Bond
- 17: Record (Suffix) Symbol for Manufacturer [44]

The American standard specified the grinding wheel as:

- Abrasive type (A)
- Grain Size (60)
- Grade (Q)
- Structure (8)
- Bond Type (V)
- Manufacture's Identification Number (25).

V. SURFACE INTEGRITY

Surface integrity means the geometric features of surfaces. It also describes the mechanical and metallurgical properties and characteristics of machined surface. In manufacturing operations, surface integrity is the most important consideration because it can influence the fatigue strength, corrosion resistance, and product service life. Various defects caused by surface integrity, such as (a) defects in the original material, (b) the method used for production of surface, (c) Improper control of process parameters. [41]



Surface characteristics (Courtesy, ANSI B46.1 - 1962)

Fig.1.9 Surface Structure Terminology [41]

5.1. Surface Roughness

Surface roughness is specified as the nearly separated irregular deviations on a scale. Surface roughness is lesser than the waviness and it is measured in terms of its height, its width, and the length of the machined surface. [5-8]

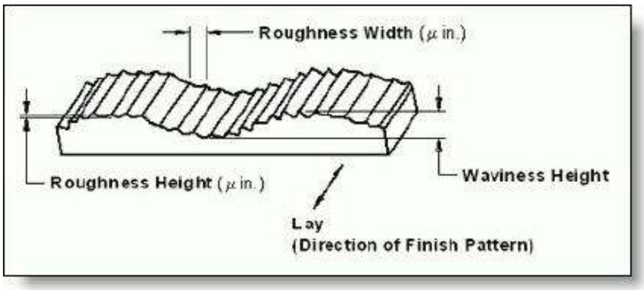


Fig.1.10 Surface Roughness [41]

5.2. Surface Roughness Measurement

Measurements of surface roughness and for recordings, Surface profilometers are used. A “Diamond stylus” instrument is most commonly used which travels along a straight line, over the workpiece surface, as shown in figure. Stylus travels at a specified and controlled distance; this distance is called as Cutoff. This recording instrument indicates only roughness. Profilometer traces the roughness and record it on a vertical scale, called a gain of the instrument. Mechanical and electronic means are used to record the surface profile. [10-15]

Fig. 1.12 Surface Roughness Tester

VI. MATERIAL REMOVAL RATE (MRR)

Material Removal Rate (MRR) is defined as the ratio of volume of material removed to the machining time (i.e. Time taken to remove the material).

$$MRR = (Wb - Wa)/Tm \qquad \text{……… (I)}$$

Where, W_b = work piece material weight before grinding
W_a = work piece material weight after grinding
Tm = machining time (Min/Sec).

During the grinding of work piece at each region, the weight of the specimen is measured before grinding at one region, and time is noted during grinding at particular region. After completion of grinding at each section, the work piece is removed and the weight of the work piece is measured after grinding. [6, 11]

VII. CYLINDRICAL GRINDING TERMINOLOGY

The following terminology is used in the cylindrical grinding process as shown in Fig. 1.13.

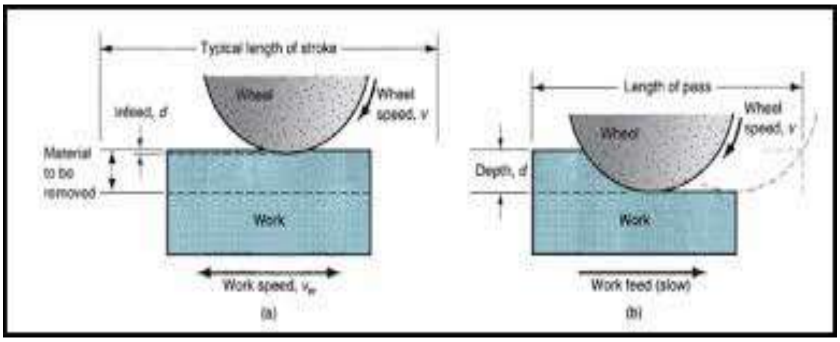


Figure 1.13 Illustrations of terminology [44]

- **Grinding Speed:** It is the comparative peripheral angular velocity of the abrasive wheel with respect to the work piece. The measurement unit of grinding speed is measured in meter per minute (mpm) or meter per second(mps).

- **Grinding Feed:** It is the longitudinal motion of the work material relative to the axis of abrasive wheel as per rotation. It is measured in mm/revolution.
- **Grinding Force:** The Force exerted by grinding wheel on a work material surface is known as Grinding Force. It is taken in kgf.
- **Depth of Cut:** It is the thickness of the work material layer took away in individual transcend. It is generally measured in mm.
- **Arc of Contact:** The small portion where abrasive grains actually contact with the work piece of a grinding wheel.
- **Grinding Direction:** The direction towards which the grinding wheel moves on the work piece surface.
- **Surface roughness:** Surface roughness is specified as the nearly separated irregular deviations on a scale. Surface roughness is lesser than the waviness and it is measured in terms of its height, its width, and the length of the machined surface. It is measured in μm.
- **Swarf:** Grinding wheel particles and workpiece material particles generated during grinding is called Swarf.

VIII. FACTORS AFFECTING SURFACE FINISH DURING GRINDING

- **Grinding Force:** As grinding force between grinding wheel and specimen increase the surface finish increases up to an extension after that cutting of material starts. [5]
- **Grinding Speed:** Surface finish increases with grinding speed.
- **Grinding Feed:** Surface finish increases with grinding feed, but up to a limit point.
- **Lubricant:** With the use of lubricant during grinding the surface finish increases.
- **Number of Passes:** Surface finish increases with no. of passes, but after some definite passes it becomes constant.
- **Hardness of Abrasives:** As the hardness of abrasive particles increases the surface finish produced also increases.
- **Surface Condition of grinding wheel:** If the grain size of abrasive particles is coarse it will produce rough surface. If grain sizes are very fine so it will produce finished surface. So surface finish is directly proportional to the dressing of the grinding wheel.
- **Initial Condition of Surface to be Ground:** If the surface is rougher, the percentage of improvement in surface finish will be more.

IX. PARAMETERS OF GRINDING OPERATION

Major process parameters which are most commonly used in grinding process are machining speed, feed rate and depth of cut.

9.1. Cutting Speed

It is the comparative peripheral angular velocity of the abrasive grinding wheel with respect to the work material. The mathematical formula used to calculate the cutting speed is:

$$V = \frac{\pi . D . N}{1000} \text{ mpm (meter per minute)} \qquad \text{…………..} \textit{(II)}$$

Where,
D = DIA. of grinding wheel (mm),
N = grinding wheel revolution (rpm)
V = Cutting velocity of wheel (mpm).

9.2. Feed Rate

It is the longitudinal apparent motion of the work material relative to the axis of abrasive wheel rotation. It is measured in mm/revolution. The feed rate is used to compute and estimate the total time taken for grinding. For rough grinding, maximum feed rate is kept up to 0.9 times of face width of abrasive wheels and for finish grinding; the feed rate should be up to 0.6 times of grinding wheel face width. Feed rate cannot be equal to or greater than the width of abrasive wheel. The total time taken for grinding process can be calculated by following equation;

$$T = \frac{L \times I}{S \times N} \times K \qquad \text{……………..} \textit{(III)}$$

Where
T = time taken for grinding (min)
L = longitudinal travel (mm).
I = number of passes
S = feed rate (mm/rev.).
N = Grinding wheel revolution (RPM) and
K = coefficient depends upon the designated degree of accuracy and level of surface finish
Values of coefficients generally taken for rough grinding, K = 1 to 1.2; and for finish grinding, K = 1.3 to 1.5.

9.3. Depth of Cut

It is the thickness of the work piece layer removed in individual exceed. It is generally measured in mm. It is maintained ranging from 0.005 to 0.04 mm normally. For precision grinding, smaller depths of cuts are set. [27-28]

X. RESEARCH TRENDS IN GRINDING

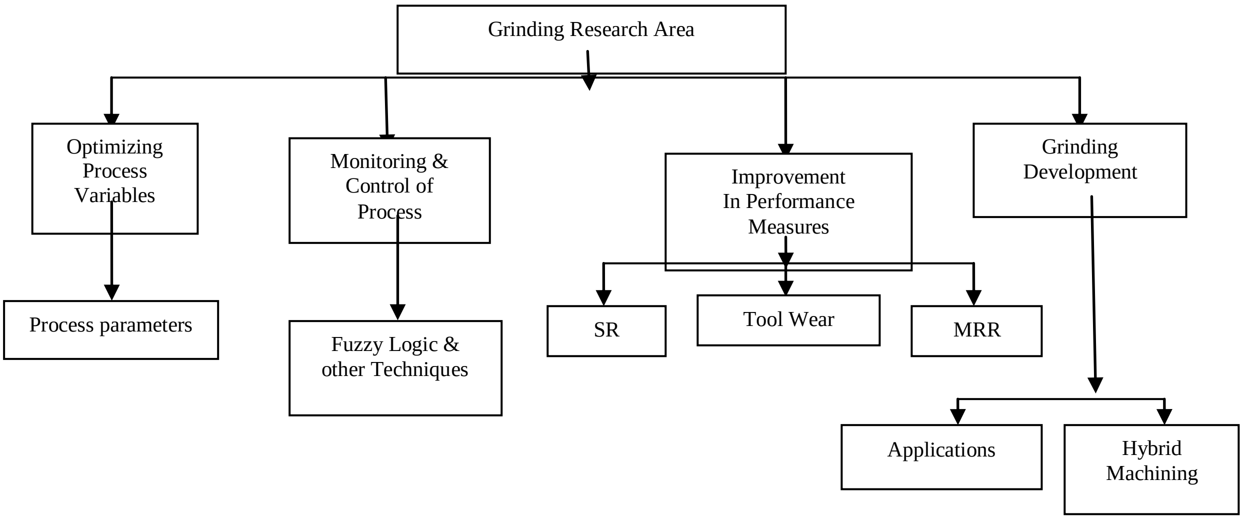


Fig: Classification of Major Grinding Research Area

10.1. Literature Review

Grinding is considered a precision material removal process. Norton, Charles Hotchkiss invented the cylindrical grinding machine in 1886. In 1919, cylindrical grinding machine had become a standard machine tool in automotive plants. The grinding owes lots of its evolution from the Industrial Revolution, especially to the advancement reliable, less expensive steel production and later the advancement of the grinding wheel.

Stetiu et al researched that, in cylindrical grinding, wear or fatigue rate is an interior part of the operation. The external cylindrical grinding machine was used to perform the experiments. Experiments were performed on cylindrical steel rods having 0.5% carbon and Hardness of 52 HRC. Grinding wheel specification, Aluminum oxide (Al2O3) vitrified bond grinding wheel having different hardness and grain size of 40 µm had been used. The research work resulted that the hardness of an abrasive wheel affects the wear rate. Tarbekin et al has brought surface roughness significant to our attention. In Medical Products, surface roughness have been one the most important quality measures (Chang, 2001). The impact of two factors, namely the depth of cut and work piece materials on surface roughness is depicted in (Grover, 1996).

Design of experiment (DOE) is the first step in any experimental work. R.A Fisher introduced a statistical technique in 1920's. The objectives of the design of experiments are as follows:

1.) Study the effect of multiple variables simultaneously.
2.) Optimize the process and product design.
3.) The effect of different factors on the process.
4.) Impact of individual factor in the performance of another.
5.) Determine the factor that has more influence. [5-8, 26-28]

Midha et al proposed that the determination and choice of grinding parameter selection still depend particularly on operator skills based on his technical cognition and work experience. This is because; the knowledge resource is not consolidated, not easily available to the industrial user and frequently not easy to use.
Most of the researchers used Taguchi method and response surface design methodology (RSM) in metal cutting process parameter optimization problems such as;

Guoxian et al proposed a self-governing system for the multistage cylindrical grinding process. Optimization scheme was planned to minimize grinding process duration while fulfilling generation requirements. The experiments were conducted on Bryant Model H 16 internal grinding machine with a personal computer on AISI 52100 alloy steel. Experimental work pieces had 0.98% alloy steel rod of hardness 60 HRc. Grinding wheel having specification 32A80L6, wheel DIA. 25, 50 with a medium structure were used. The research work presented the validated strategy in simulation and for actual grinding tests. [9]

Youssef et al proposed & compared the conservative advantages of Taguchi strategy and partial factorial investigations with a full factorial outline system in machine turning operations. Lee et al provided an interactive algorithm to solve optimization problems in turning operation using mathematical modeling and Response surface Methodology and mathematical modeling. [8]

Shih et al recommended that the increase in the abrasive wheel velocity decreases the normal chip thickness and increase the hardness of the abrasive wheel. AGN5 Cylindrical Grinding Machine was used to perform the experimental work and grinding wheel having vitreous bond CBN was utilized. He concluded that the normal and tangential forces reduce as the abrasive wheel velocity increases and also increases the surface finish of Zirconia and M2 steel metals. Ali et al proposed the surface roughness forecasting of ground surface created by surface grinding operations, using Fuzzy logic approach. In this study, they revealed that though surface roughness is one of the most significant factors. The difficulty originates from the way that numerous factors influence the procedure. These factors include: the work material properties, abrasive wheel composition, dressing conditions, working parameters, coolant properties and machine vibration. [1]

Murthy et al proposed that the hardness of the ground steels is likely to drop sharply with rises in temperature beyond 4000-5000C due to over tempering. On the other hand the austenite manganese steel gets work hardened and the hardness rises sharply due to the transformation of austenite into martensite. Hon Zong Choi et al proposed the effect and advances of the use of coolants during machining, he concluded that the grinding efficiency improves if the coolant contains chlorine, sulfur, and phosphorus but these ingredients cause pollution and harmful to the workers. White Alumina (WA) and a CBN wheel were used to perform the experiments. The dry grinding and wet grinding with coolant were compared. Suresh et al predicted the optimal machining condition for good surface finish and dimensional accuracy by using a Genetic algorithm. A surface roughness prediction model for turning operation of mild steel was developed using Response Surface Methodology (RSM). The combination of high speed, low feed, with moderate depth of the cut and nose radius produced better surface roughness and metal removal rate and minimizes the machining time. [39]

Yang et al utilized the DOE Taguchi method to optimize the material removal turning operations process parameters. They resulted that the tool life's is mostly pretended by the machining speed of the tool. The authors resulted that the grinding wheel speed, feed rate and depth of cut are the substantial machining parameters for surface roughness. Rogelio Hecker et al conducted a serried of experiments on a cylindrical grinding machine. He concluded that the nature of the surface created by cylindrical and surface grinding decides work piece qualities, for example, the lubrication effectivity and the material life, among others. [37]

Hassui et al suggested that, the wear of an Abrasive wheel directly affects the work piece vibration and both have the impact on the work piece quality. Experiments were carried out on a plunge cylindrical grinding machine. AISI 52100 quenched and tempered steel (58 HRc) material was used. The aim of the research was to compare and study the relation between vibration signals and the quality of work piece (i.e. mean roughness, circularity, and burning). Manna et al conducted the experiments on aluminium and silicon carbide based metal matrix composite utilized. Taguchi method was exploited to determine substantial cutting parameters setting to accomplish more proficient surface finish during turning operation. [5-8, 26-28]

Ghani et al utilized Taguchi method in the optimization of end milling process parameters and found that the optimum combination of low resultant machining force and good surface finish in milling parameters are high cutting speed, low feed rate and low depth of cut. Kwak et al effectively applied Taguchi method for experimental analysis and optimization for the process parameters essence on a geometric error in surface grinding process and developed a mathematical model by Response Surface Method (RSM) for forecasting the geometric error. It was found that geometric error is caused by the low levels of depth of cut, Abrasive grain size and the middle levels of abrasive wheel speed and table speed. [24]

Aggarwal, et al analyzed the result of cylindrical grinding parameters such as machining speed, feed rate, depth of cut, nose radius and cutting environment on power expenditure. They conducted the experimentations on CNC turning by using AISI p-20 tool steel. In their study, significant parameters in achieving minimum power consumption were analyzed using Response Surface Methodology (RSM) and Taguchi's technique. Janardhan et al suggested that the surface roughness (SR) and MRR are the most significant responses. The experiments were conducted on the EN8 material (BHN = 30-35). CNC cylindrical grinding machine was used to perform the experiments. He concluded that the feed rate is the vital parameter for surface roughness and material Removal rate. Jingzhu Pang et al proposed heat distribution model by using CBN grinding wheel and Ti-6Al-4V material to calculate the heat flux with measured temperature. [24] Wang Pei Zhuo et al presented the effect of residual stresses on Inconel-718 and concluded that by embedding source of heat with material, tensile residual stress can be transferred into compressive stress. [25]

K. Mekala et al demonstrated the consequence of machining speed, feed rate & depth of cut on SR and MRR of AISI 316 steel material. The author resulted that the machining speed has the important significant essence on SR while the depth of cut has a higher impact on MRR.
M. Kiyak et al concluded that the higher workpiece spindle rotation and low feed had most substantial parameters for surface roughness. The author investigated the effect of workpiece spindle rotation & feed rate by using AISI 1050 steel under dry conditions. [24]

Rodrigo Daun Monicia et al concluded that the united function of neat oil & CBN wheel increased the efficiency. [36] H. Saglam et al presented the effect of depth of cut, work piece speed & feed rate on AISI 1050 steel to measure the roundness error and SR. Author concluded that the value of surface roughness improved by the higher value of wheel speed and lower value of feed rate & depth of cut. [10] Arshad Noor Siddiquee et al optimized the seven process parameters of in-feed grinding by using the Grey relational analysis method on EN 52 austenite valve steel. [3]

Summary of Literature

The summary of the literature indicates that most of the research work is concentrated in the area of force measurement, product quality analysis, tool condition monitoring, and the development of mathematical model and optimization of machining parameters in the metal cutting operations In gathering a good surface finish, grinding machining used in the production is an important part of the machine tool trade to improved machine construction has permitted the production of parts to extremely fine tolerances with improved surface finish and accuracy of the finish product. Because of the dimensional accuracy obtained by grinding, interchangeable manufacture has become commonplace in most industries. Julie, 2007 stated that it is difficult to compute the value of surface roughness through theoretical calculations because the mechanism behind the establishment of surface roughness is very dynamic, preplexed, and operation dependent. So other method like Design of Experiment (DOE) has been using for the analysis. In many cases, grinding eliminate the need of conventional machining. A new development of abrasives and better machines, the rough part is often finished in one grinding operation can reduce the need for other machining. Nowadays, grinding is applied extensively to productions of unhardened parts where high accuracy and surface finish. Design of Experiments (DOE) is the most powerful tool currently available for researchers and it helps in design an experiment that will provide the most information with the least amount of work. In order to analyze the data, the fractional factorial design as a method in DOE to study, which surface grinding parameters that influence surface roughness of the work material. The parameters clarify to be studied in this project is workpiece materials, depth of cut and feed rate. Most of these developments are focused on turning, milling, drilling and surface grinding due to the inherent facility available. The understanding of the grinding parameters and their relation to the responses in cylindrical grinding, are still limited and yet to be studied. The factors that have been outlined in the literature have considered, exploring the changes on the selected responses in cylindrical grinding.

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