Design and Development of a Diamond Disc Precision Cutting Machine

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I certify that this research work titled "*Design and Development of a Diamond Disc Precision Cutting Machine"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Abstract

With the advent of technology, the demand for high performing materials is always increasing. Automotive industries, Aerospace industries and other high performance industries are always in search of materials that provide with high strength values. The industry craves for materials with high strength values and low weight to gain advantage in high performing applications.

For this purpose, numerous studies have been performed to search for materials that have good strength to weight ratio and possess material characteristics that can sustain the high-performance conditions.

Titanium and Inconel are an example of such materials. Titanium alloys have found use in several industrial applications where high performance is expected of a material while not increasing the weights. Titanium Alloys have gained good popularity in this regard however the metal has known to be very challenging when it comes to machining. Titanium has very low conductivity hence the heat produced while machining is not dissipated easily which causes tool damage.

Machining (Subtractive Manufacturing) is one of the most prominent methods of manufacturing till this day and is the most widely adopted mode of manufacturing to get increased production rates. Machining generally involved the chip removal of a workpiece layer by layer to obtain a required geometry which causes tool wear specially in case of Titanium as discussed and induces Sub-Surface Damage to the workpiece.

Metal Cutting is an essential component of the manufacturing facility and since all operations induce some damage it is critical to optimize manufacturing processes to minimize damage induced.

Key Words: Machining, Diamond Disc, Cubic Boron Nitride, Sub Surface Damage, Titanium.

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

The research work in this dissertation has been presented in two parts. First part relates to the Introduction and Literature Review while the second part is focused on the design and development process of a diamond-disc precision cutting machine.

1.1 Background, Scope and Motivation

High strength materials with low weights are becoming a prime consideration of all manufacturing sector industries with each passing day. Be it the Aerospace industry or the automotive sector, shipyards or robotics, all aspects of modern-day technology crave low weight materials while not compromising on the strengths. This unique demand has forced researchers to study and discover numerous materials that may function better or even create their own materials such as composites.

One aspect that yet remains troublesome is the machining and processing of these materials. Not all materials are easy to machine nor are these materials processed in similar fashion. Machining poses a great challenge to the manufacturers. Finding a suitable combination of parameters which minimizes the wear of tool as well as causes minimal damage to the workpiece itself is a formidable task. Titanium is one such material that provides very high strength to wight ratios. From Aerospace to Biomedical, Titanium alloys have found use in numerous applications. Efficient machining of titanium without causing much harm to its structural integrity can push these industries to the next level.

1.2 Manufacturing

The term manufacturing refers to the conversion of any raw material into a useful geometric part. Considering metal manufacturing, there are several processes and techniques that are adopted for shaping metal into a required geometry. A few common manufacturing techniques often adopted by the industry are as follows:

1.2.1 Forging

Forging is a manufacturing technique that requires for a metal piece (Billet) to be heated up to a point where it is red hot. This red-hot workpiece is then hammered into a shape or forced into a die.

1.2.2 Casting

One of the most ancient of all the metal manufacturing techniques is Casting. The process requires for a metal to be heated beyond its melting point to bring it into a molten state. This molten metal is then poured into a mold which is pre-set as per the required dimensions. After cooling off, the metal is set into the shape of the mold, which is then extracted.

1.2.3 Forming

Forming, as indicated by the name itself, is a process of bending the metal into a desired shape. The process requires for a pressure to be applied upon a metal for it to be shaped as per desire by the formation of a crease. Sheet metal forming finds use in the making of the external body of several machines and automobiles.

1.2.4 Machining

Machining is one of the most common of the manufacturing processes which requires for a metal to be shaped into a required part by machining out the extra metal from the work piece. The method requires for a suitable tool to be used with a proper feed and depth of cut, along with other parameters to cut of metal surfaces from a workpiece to bring it down to a required shape and size. Lathe and Milling are two most common processes for machining.

1.2.5 Cutting

On the surface, the process is nothing but cutting of a large metal piece into a smaller piece, however the process may become intricate and involved once the requirements start to get specific. Several cutting techniques are used these days such as saw cutting, power scissors, plasma cutting, laser cutting etc. These techniques are all adapted for one purpose only, cutting of larger metal pieces into smaller ones, however the end product properties and the process capabilities may be very different.

1.2.6 Additive Manufacturing

Additive manufacturing is one of the most recent advancements in the world of manufacturing and has revolutionized the concept of Rapid Prototyping. The process is entirely opposite of the Machining and requires for a desired geometry to be built up from scratch. The process requires for the end product to be built up layer by layer by deposition of material. The process was earlier used only for polymers however it has now found uses in metal as well by fusing metal powder using laser to create end product in layers.

1.3 Subtractive Manufacturing

Subtractive manufacturing is the most widely employed technique in all industries. The process involves removal of chips and layers/pieces from a workpiece in order to create a product in accordance with the required geometric specifications. Being the most common and fastest mode of manufacturing, Subtractive manufacturing attracts all industries.

With huge demand of the technology comes the prospect of research and optimization. Several researches have been conducted on numerous processes and materials in demand in order to identify the parameters that provide the most suitable and efficient results.

Numerous challenges associated with subtractive manufacturing have been addressed lately in pursuit of optimizing the manufacturing process.

1.3.1 Recent Advancements

Recent researches have shown different operating parameters that can optimize the process in order to increase the tool life and improve the quality of workpiece surface finish. Heat during machining can cause the tool to wear off. Workpiece surface also gets affected by heat creating a heat affected zone where the properties of the materials may differ slightly.

Machining speed, in terms of tool speed and feed can also affect the quality of the end product,[1] hence the researchers are always in pursuit of better operating parameters and tools for different in demand materials such as Titanium, Inconel etc.

Q. An [2] in their study on the effects of Cold Mist Jet (CMJ) on high speed Cutting of titanium Alloy concluded that the CMJ method of coolant was indeed better than flooding the machined surface with coolant. They found CMJ to be twice as effective as flooding and fifteen times more effective at Transient Heat Transfer than Air Cooling. Furthermore, the tool life was also found to have increased with the application of CMJ rather than Air Cooling or Flooding at different cutting speeds ranging from 38 m/min to 120 m/min.

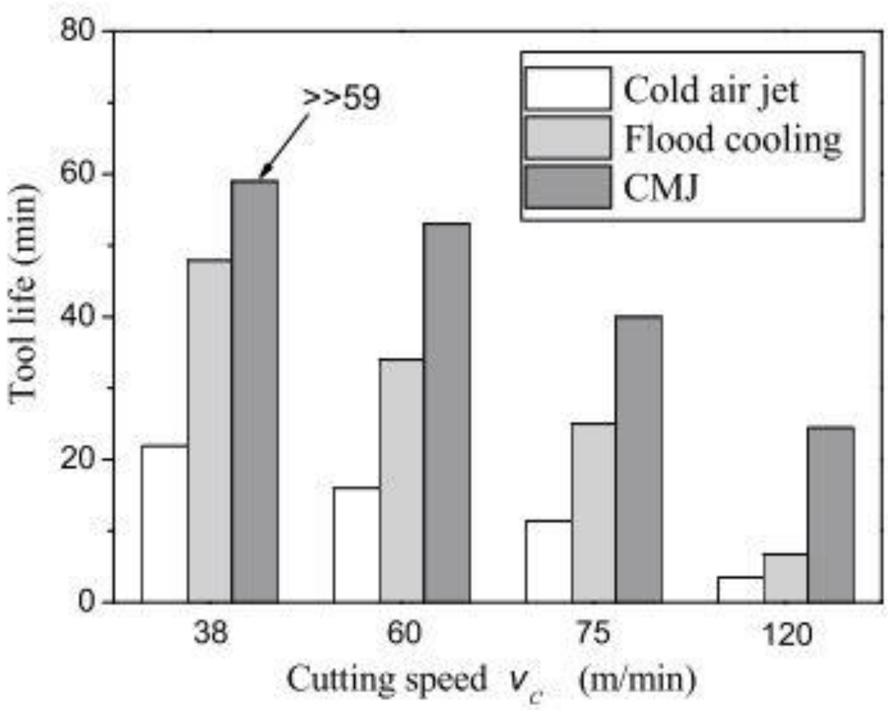

Figure 1: Tool Life comparison at different cutting speeds using different cooling methods

Surface roughness on the contrary is observed to be less in case of flooding while the CMJ shows slightly more surface roughness.[2]

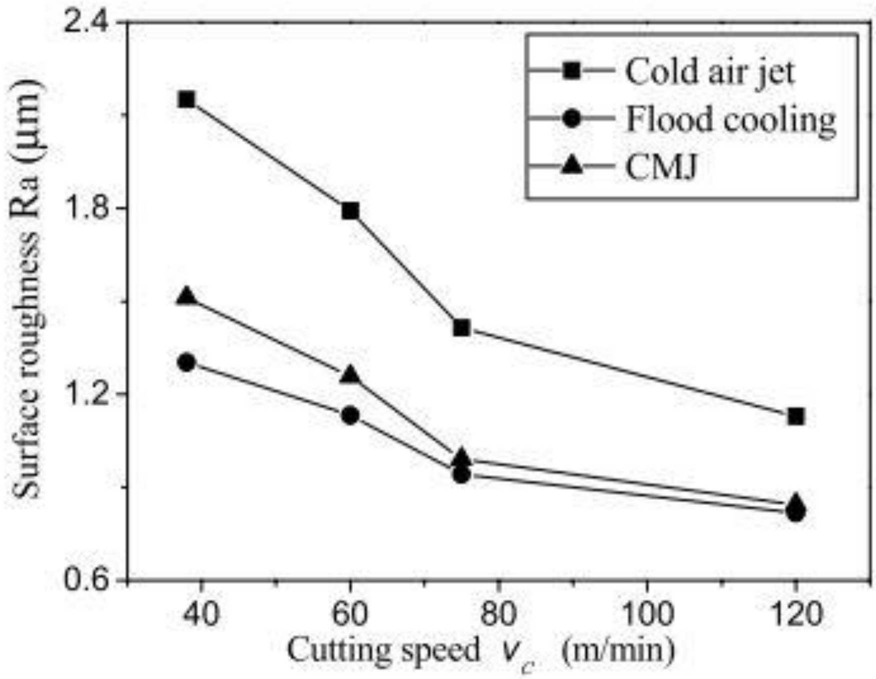

Figure 2: Surface Roughness vs Cutting speed
under different cooling conditions

Another study dedicated to address the heat damage to the tool while machining of Titanium alloys was performed by E.A. Rahim [3] who investigated the effect of Palm Oil on the drilling operation of Titanium Alloy. MQL lubrication technique was adopted for high-speed drilling using palm oil. The study also concluded for the MQL-Palm Oil and MQL-Synthetic Ester Lubrication to be better than flooding machining conditions.

1.3.2 Machining of Titanium and Challenges

Titanium is one of the most in demand materials these days. The metal and its alloys have a very good strength to weight ratio. High strengths with half the weight as that of steel, Titanium finds use in several industries such as Automobile, biomedical, Aerospace, Marine, etc.[4]

While being a metal with many uses and attractive strength, the metal poses a huge challenge to the manufacturers as machining of titanium proves to be very taxing. Titanium has a very poor heat conductivity hence the heat generated during machining of the relatively hard metal, Titanium, cannot be dissipated easily. Usually while machining, in other metals, the machining heat generated is dissipated by conduction in the workpiece itself however in titanium the heat is localized to the tool-workpiece interface only which causes for the tool to wear out and workpiece to get damaged as well.[5]

Owing to the low elastic modulus, machining of titanium is often faced with a spring back action of the material which causes poor surface quality and tends to wear off the tool. [6]

Machining often tends to induce sub-surface damage to the workpiece while removal of chips. The surface being removed by the tool is often removed by plastic deformation by the tool which causes for the layers directly beneath the tool interface to be deformed and hence sub-surface damage is induced. [7]

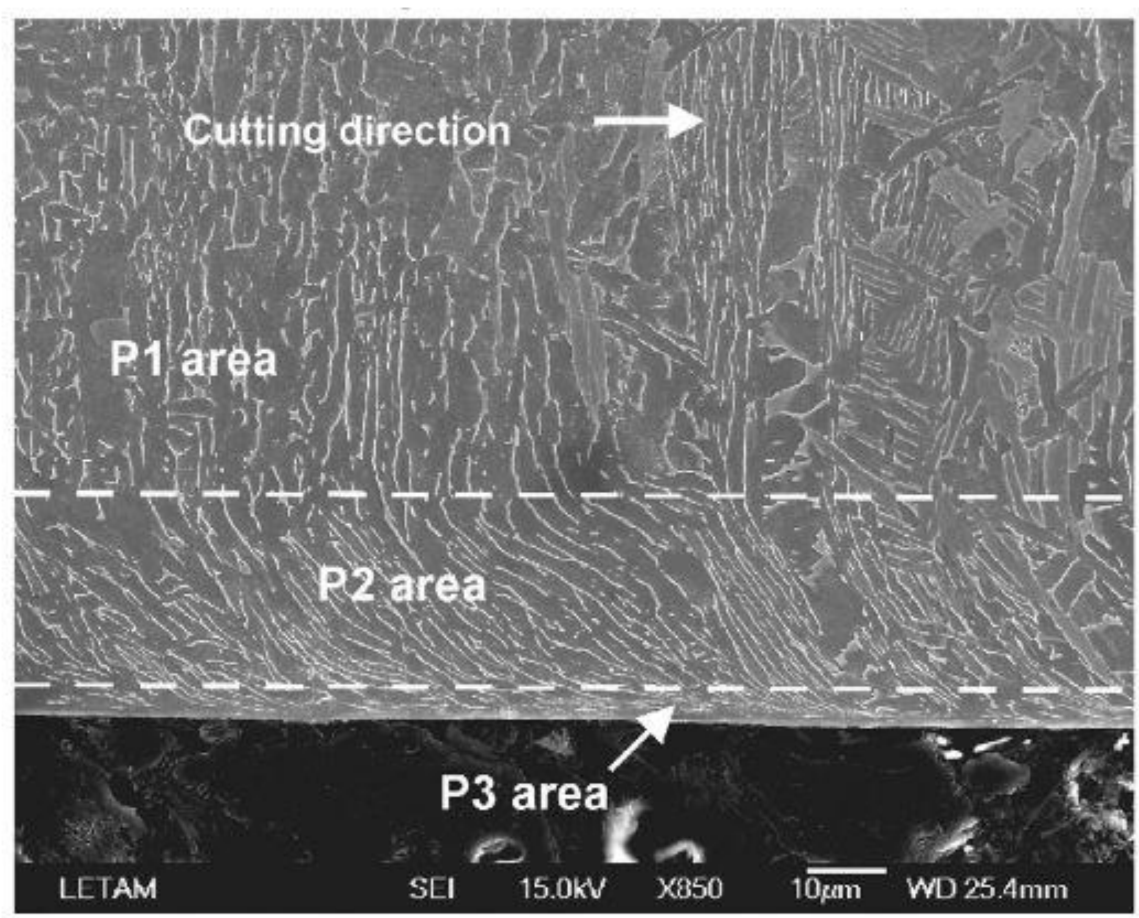

Figure 3: Damage induced by Orthogonal Cutting on CNC Lathe

The above given image of orthogonal cutting of a CNC Lathe Machine shows the induced damage in the workpiece while machining. It can clearly be seen in the zones P1, P2 and P3, how the grains have been plastically deformed beneath the cutting surface and the depth of the damage induced.[7]

Several researches have been conducted to identify the effects of numerous operating parameters such as the tool speed, the coolant applied and depth of cut to identify the parameters that induce the least subsurface damage to the workpiece.

Cutting speed has been noted to affect the surface integrity of the workpiece. The cutting speed may influence the plastic deformation of grains in the direction of the cut. Other parameters such as the tool wear, surface roughness and debris are also affected by the cutting speed of the tool. [8]

CBN tools such as Diamond Disc are found to be effective at machining and cutting of Titanium metals [9]. In this project we aim to design and develop a Diamond Disc Precision Cutting machine which would also be able to cut Titanium Based Alloys. Significance of the Titanium metals and their machinability has already been established. The ever-growing need of high performance materials creates a research prospect to find materials which are most reliable under heavy load conditions due to their strength while have minimal load.

There is a need to find materials and machine them with optimized machining parameters to induce minimum damage to the material so that its performance is not hindered.

A Diamond Disc precision cutting machine will assist in this regard by providing with precise cut and by assisting with the studies and analysis of the effect of machining parameters on the workpiece.

Minimizing all damages associated with the machining and cutting operations by the interaction of tool is a vigorous challenge and needs continuous research that keeps manufacturing processes optimized.

CHAPTER 2: METHODOLOGY

Methodology for the project is as per the general product design and development parameters. The project was completed through various stages such as Concept design, Survey for availability of parts and their dimensions, preparation of CAD Model, Fabrication of the designed machine and its Testing.

Figure 4 Methodology Flow Chart

The project was started initially with a detailed literature review of the machining process, specifically of titanium alloys. Effects of certain machining parameters on the surface integrity and tool life were studied.

Optimization of Operating parameters play a critical role in extending the tool life and minimizing the machining induced damages to the parts. These parameters established were decisive when it comes to the development of the diamond disc cutting machine.

Having enough literature review and a decent understanding, we moved towards the designing phase. Designing phase is where concept of the machine was prepared, and market was surveyed for the availability of parts and their specifications. Refined CAD Model was prepared followed by which the fabrication started.

All parts were fabricated as per the specifications decided in light of literature and market reviews.

Having successfully developed the machine, a series of Tests were performed in order to ensure the quality working of the machine. Metal Parts were cut and the vibrations were analyzed.

CHAPTER 3: DESIGN AND DEVELOPMENT

With a motive to design and develop a Diamond Disc Precision Cutting machine, the project was completed in different Stages i.e. Concept design, CAD Modelling, Market Surveying for availability of standard parts, Refining the CAD Model, Fabrication, Assembly, Testing and Improvements.

3.1 Concept Design:

The concept is to prepare a diamond disc precision cutting machine where the cutter is stationary while the workpiece is mounted on a movable arm that slowly drops the workpiece on the cutting plane causing the workpiece to be cut smoothly with self-weight under the feed provided by gravity.

The Diamond Cutting Disc (CBN Coated) is a very low thickness disc of brittle nature. This tool breaks while cutting under the influence of vibrations. In order to avoid this scenario, the machine is required to have very low vibration levels.

CBN Tools are known to work well while machining titanium. A good surface finish can be achieved with rather low fatigue and cutting forces however the process of machining titanium is very thermally dominant as discussed earlier hence the CBN coating may wear off due to aggressive tool-workpiece interface.[5][10]

A precision screw will be utilized to adjust the workpiece precisely on the cutting plane after which the position of the workpiece will be locked and the test sample will be cut under the influence of its weight. Since the sample is being cut slowly under the feed provided by gravity (or some added weight to the lever) the sample shall be cut smoothly with minimal vibrations and less heat of operation.

CBN Coated discs, more commonly known and referred to as the diamond discs, may get damaged under high temperatures. Generally, tool wear increases as the temperature of the machining is increased [11]. The machine is being designed primarily for the cutting of Titanium based Alloys which are hard metals and do not possess a very good heat conductivity due to which the localized heat at the tool-workpiece interface is high resulting in massive tool wear. Therefore, it is crucial for the cutting temperatures to be kept low. A cooling pump along with a suitable coolant may be employed for keeping the working temperatures of the cutting operation to a minimum in order to ensure least possible damage to the tool as well as to the workpiece itself.

Precision cutting required for the operation to have minimal vibrations and a very streamlined power during operation. The load conditions may vary during operation which may in turn cause fluctuations in the RPM of the machine. The solution to this problem was proposed by using either a Variable Frequency Drive (VFD) coupled with an encoder to monitor the rpm of the operation using a feed back loop system or to use a Servo Motor with a compatible controller drive that monitors the rpm and ensures no drop occurs under load.

The setup can be made such that the machine consists of two major compartments. One for the Drive assembly where motor and the controller are mounted, and a panel is given for setting controls as required. An RPM display shall be used to monitor the current readings of the operation. Second compartment is for the cutting operation itself where the cutter is mounted on a shaft and a screw assembly to control position of workpiece is installed.

A coolant tray may be added, if need be, under the cutter from where a small pump provides with the flow of coolant to the workpiece under operation. A grill underneath the cutter may be used to catch the cut off piece that falls off and the coolant flows back into the coolant tray.

3.2 CAD Model

After a concept, a CAD model is prepared to better understand and visualize the specifications of the machine. A better understanding of required components, their working functions, mechanisms and their proper dimensional specifications can be achieved from a quality CAD Model.

For our Diamond Disc precision cutting Machine, the CAD Model was based on the simple parameters of the size of sample that is expected to be cut using the machine and the size of the blade we expect to install. Furthermore, the material expected to be cut and required rpm of the blade also indicate the drive power and RPM required for the machine and hence the design must be made in accordance with all these specifications.

These specifications along with market constraints are the key determining factors in the dimensional specifications of all parts.

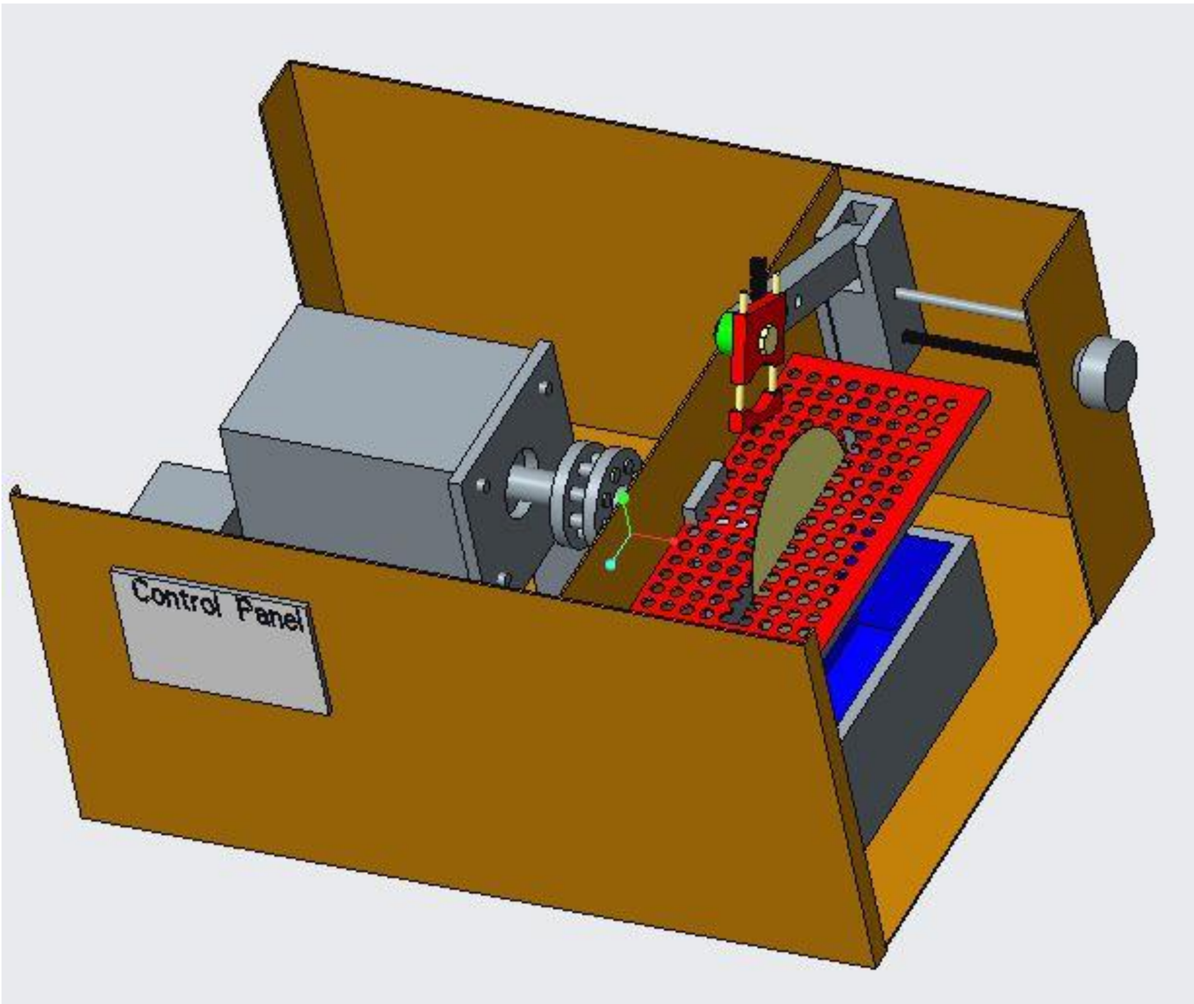

Figure 5: CAD Model of Diamond Disc Precision Cutting Machine

3.2.1 Outer Body

The outer body (609.6 mm x 455.2 mm x 300 mm) of the machine is fabricated by MS Plates of 10mm thickness welded together. The outer body along with motor foundation is expected to provide with a subtle support while operation to minimize any chances of vibrations due to the cutting forces encountered during operation.

The body is divided into two compartments, one for the drive side where the motor controller and the drive assembly is installed while the other is for operations side where cutting is to be performed.

3.2.2 Motor Foundation

The motor foundation is made heavy duty to support the weight of the motor as well as to count for the operational vibrations.

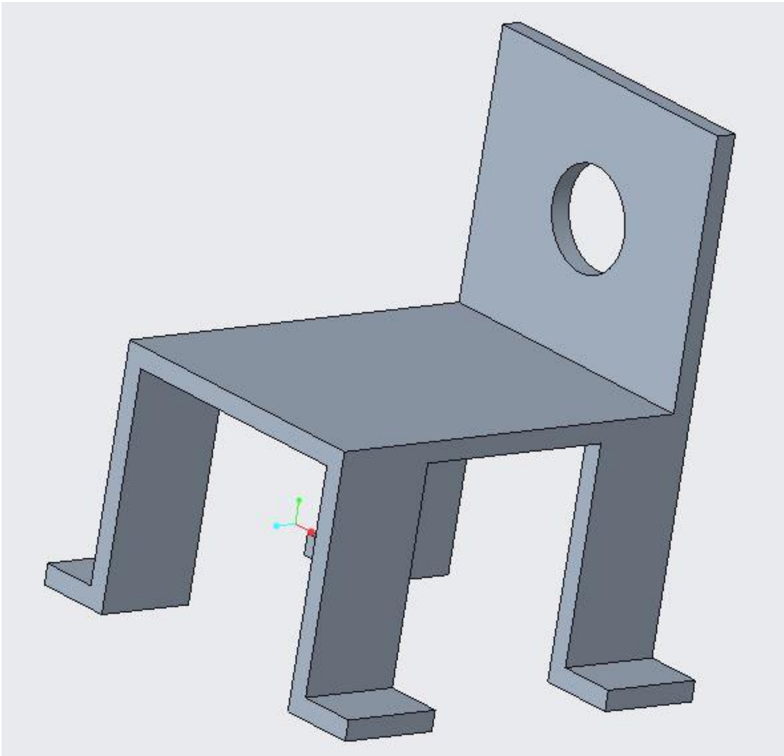

Figure 6: Motor Foundation CAD Model

3.2.3 Carriage and Feed Mechanism

A Carriage is designed to run on a feed and guide screw in carrying the arm and fixture for the workpiece to be set in. This carriage will be responsible for determining the position of cut. The carriage in intended to be light weight in order to keep it from adding much load to the feed mechanism that it rests on, yet it must possess enough strength to keep the mechanism sturdy.

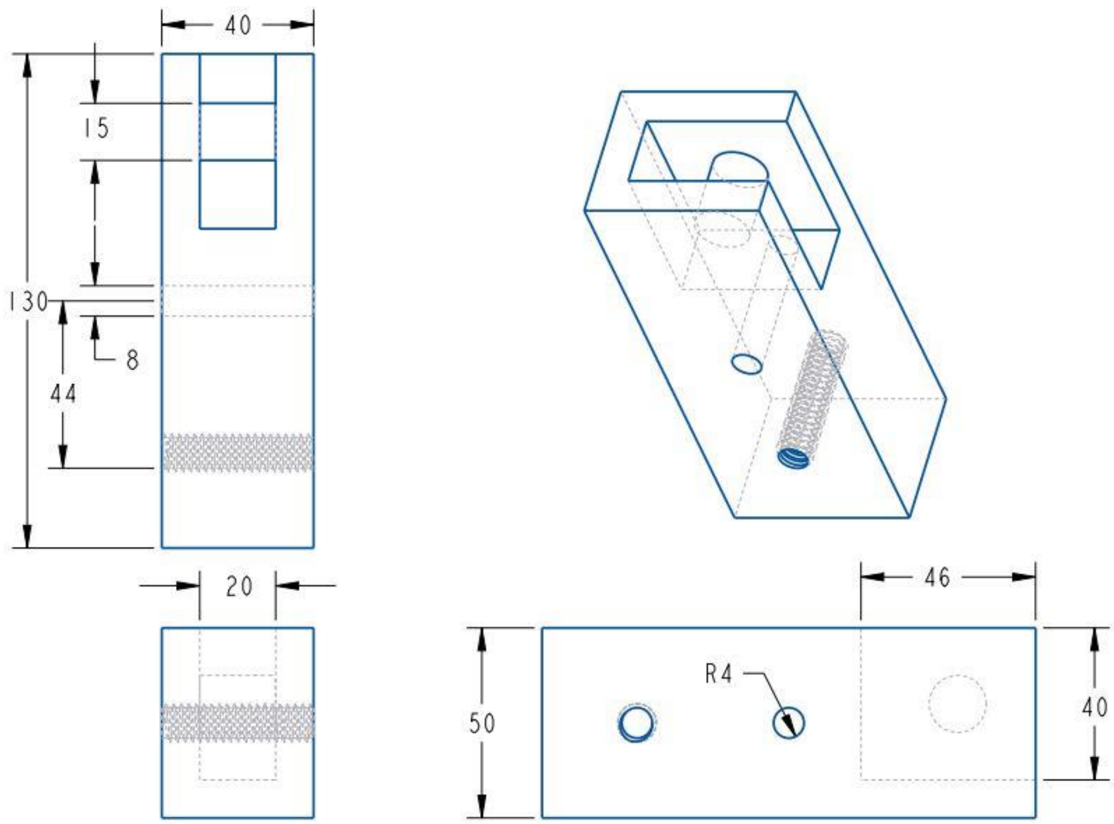

Figure 7 Carriage Design with units in mm

The Feed Screw of 2 mm pitch is used to move the carriage to a desired and suitable position on the cutting plane.

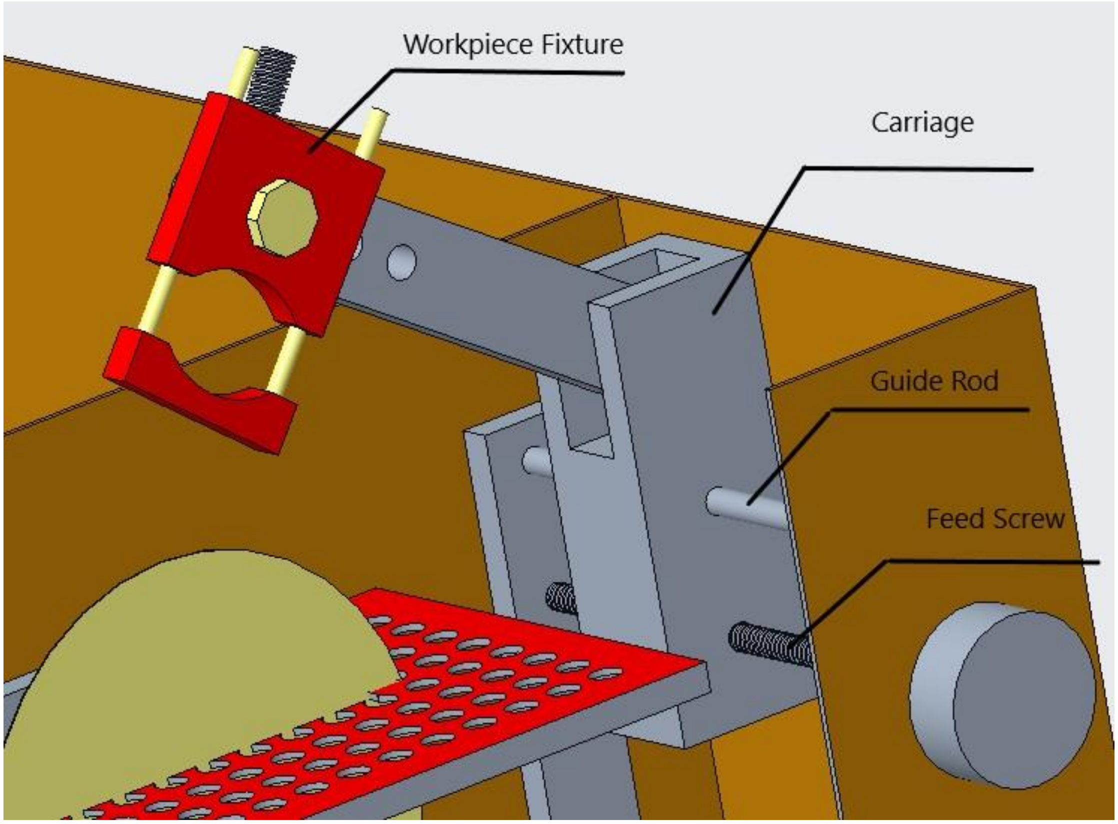

Figure 8: Feed and Carriage Assembly

3.2.4 Cutter Mount and Coupling with Drive

The Cutter is to be mounted on a shaft using two supporting cups to keep the cutter vibration free. The Shaft is coupled directly with a motor with a bearing mounted support in the dead center of the shaft.

3.2.5 Fixtures

Several Fixtures are designed to hold different types and sizes of workpiece. For Cylindrical workpiece, a curved fixture or a V shape fixture are recommended as they provide a better grip.

Figure 9: Workpiece Fixtures/Clamps

Fixtures are designed to mount workpieces on the arm to be cut under the action of gravity. The machine also allows for a user to perform cutting in the horizontal plane by using a straight surface and using manual feed to horizontally cut a workpiece.

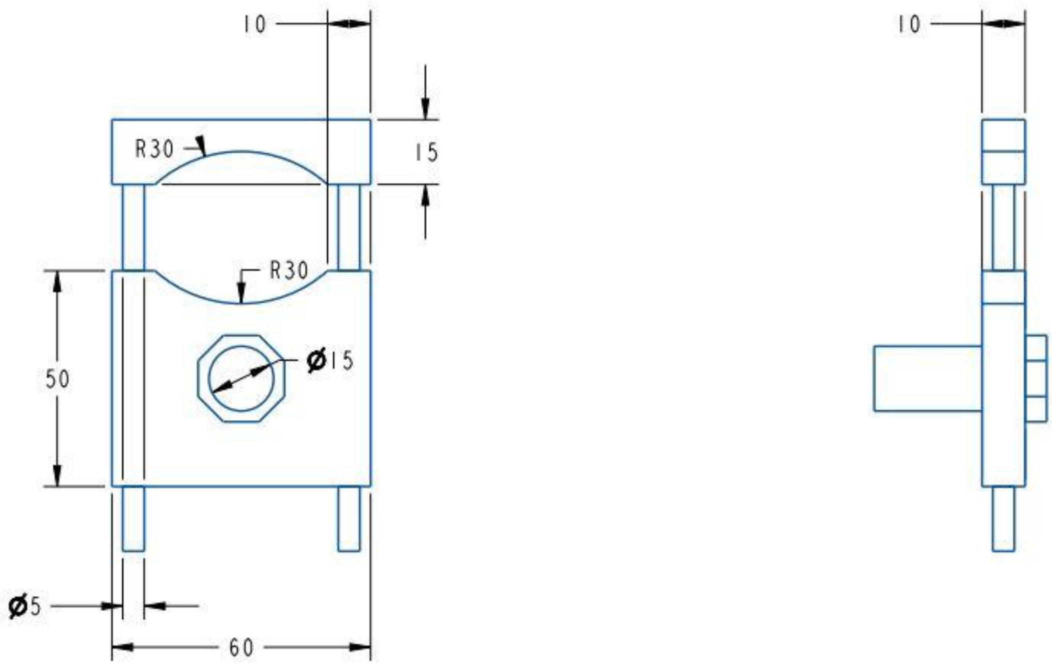

Figure 10 Fixture Drawing (units mm)

3.2.6 Coolant System

A Coolant system may be deployed for cases where higher temperature working is expected. A small coolant tank will be places under the cutter with a filter to keep metal pieces out. The coolant is to be pumped from the coolant tank to the workpiece to keep machining temperatures low and to stop any damage to the tool or the workpiece itself.

3.2.7 Safety Shield

A transparent safety shield may be used to cover the operations compartment of the machine to ensure safety of the user from any accident. This shield may be made of acrylic sheets which are transparent and will provide with a strong shield.

3.3 Market Surveying and Refining CAD Model

After initial CAD model was prepared, a detailed market survey was conducted to source all necessary parts required. The major decision was to select and procure a motor with a decent power and to develop its proper control to ensure no RPM drop under Load Conditions.

We Decided to go for an AC Servo motor over a motor controlled with VFD due to one simple reason that it provided less chance of error as it is supplied with a company provided relevant controller that has all control features pre-installed. This eased the procurement part. A 1.5 KW AC Servo Motor which came with its compatible controller was purchased. The RPM of the motor were tested under different loads to ensure the feedback system is operational and the RPM of motor are under all conditions, exactly as specified in the setpoint provided at the start of operation.

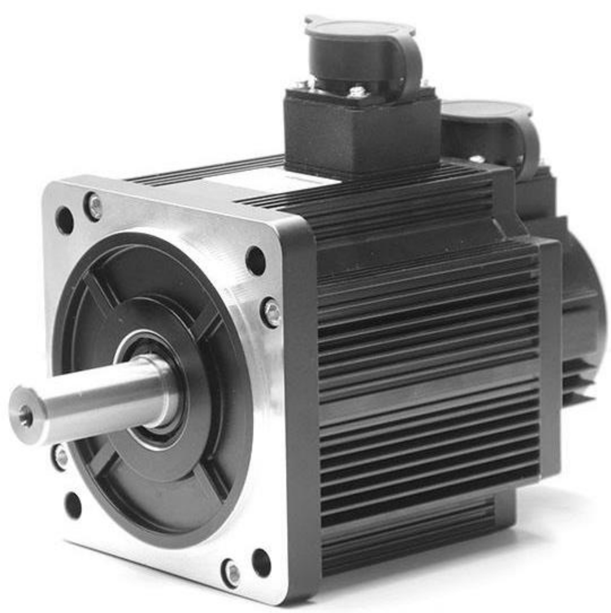

Figure 11: AC Servo Motor 1.5 KW

The Motor Purchase influenced the CAD Model by providing with some design parameters such as motor foundation type and specifications. The foundation was made such as to support the motors front mount design as well as to be at a certain height above the base plate as required by the blade diameter.

All structures were decided to be made of MS Plates of 10 mm thickness. The carriage was decided to be prepared from Teflon block due to the weight constraint as a heavier carriage resting on the feed and guide Rods may cause bending, which would in turn cause errors in operations.

3.5 Fabrication and Assembling

The fabrication jobs were performed at a private facility in Rawalpindi. The MS Plates were first pressed under weighted surface to ensure they had perfectly straight surface. The required parts were machined out by using a milling machine. The shaft and Disc mounts were prepared on the lathe machine.

All parts were fabricated at the facility as per designed model and the drawings generated.

These parts were then assembled at the NUST MRC Facility. These parts were welded together to prepare foundations and supports as per the refined CAD Model. Fabricated parts were marked for drilling holes by aligning all parts that were to be fit together.

The Motor was mounted on the structure prepared and the controller was wired to create the much-required feedback loop system to control the RPM under load.

To mount the workpiece on the cutting plane, the carriage, as intended earlier, was prepared out of a Teflon block along with its arm to keep its weight low in order to keep it from bending the guide rod and feed screw that it rests on. The fixture for holding workpiece was however machined out of an MS plate. This step was taken to ensure the workpiece was held firmly and to add weight to the fixture itself to improve feed rate of the workpiece. Furthermore, the MS fixture could be machined and welded with complete flexibility that Teflon could not provide. Another important parameter was the wall thickness after all the drilling works. A thinwalled Teflon fixture could have cracked while tightening workpiece hence it was safer to go for MS fixtures for holding metal workpieces.

CHAPTER 4: TESTING, TRIALS AND MODIFICATIONS

After completing the fabrication and assembly, the machine was operated for testing its performance. The trial was conducted using a normal abrasive cutting disc of Ø7”. Diamond Disc is usually very brittle and expensive hence the trial was conducted on abrasive cutting disc to test the performance of machine and to minimize vibrations. This also minimized the risk of accident as the abrasive disc is usually rugged and does not break easy compared to the diamond disc.

Upon testing of machine and its careful observation, a few misalignments were observed that caused vibrations in the blade which resulted in an uneven cut. The misalignments were carefully rectified.

A few modifications were made incorporating the vast experience of the MRC Staff which enabled minimization of vibrations which included removal of market purchased coupling with uneven finish on meshing parts and creating a shaft spindle with male-female locking mechanism.

4.1 Improvements in Tool Mount

The Tool Mount was improved by providing a small pocket in the discs used to tighten the tool for a better grip in order to prevent slippage.

4.2 Improvements in Workpiece Fixture

Workpiece Fixture was curved as per initial design. The curved surface provided only one point of contact for the workpiece which made it likely for the longer workpieces to slip or wobble while under load. The fixture was improved by creating a V-shape that would be more universal when it comes to holding workpieces of different diameters. The new fixture would also be more effective at gripping the workpiece as this provides with a two-point grip.

4.3 Improvements in Motor Foundation and Mount

The Motor was found slightly misaligned. After unmounting the motor, two of its alternating foundation holes were turned into grooves that would provide better flexibility for motor positioning and aligning of the motor (Face Mounted) using shims.

4.4 Testing after Modifications

After the rectification of all issues encountered with the machine during the first trial, the machine was then set out for another test after modifications. This time the machine was found to be working considerably well. The vibrations were reduced to negligible, and the workpiece was properly gripped between the V-Notch of the fixture.

The difference between the initial trial and the trial after modification can be observed by the tool interaction as the initial trial caused the tool to scrape a large surface of the workpiece due to vibrations whereas the modified version countered all issues of vibrations resulting in a better and smoother cutting plane.

Figure 12: Final Workpiece Cut

CHAPTER 5: DISCUSSIONS AND FUTURE PROSPECTS

Precision Cutting machines are frequently deployed in cases where the test samples are to be cut for studying the internal structure of a sample. Cutting machines usually used in market although provide a very fast operation, have a very crude cut and provide with a very rough surface finish. The steadfast mechanism of cutting employed in market are detrimental to the integrity of surface. These machines can be used when a metal is required to be cut without any requirement of surface finish.

Machining of metals usually induces sub-surface damage in the workpiece due to chip removal process of tool. Tool-Workpiece interaction often creates a plastically deformed zone underneath the surface due to the removal of chips. This damage of tool interaction on workpiece surface is known as Sub-Surface Damage.

Studies have explained how machining operations can be optimized such that the tool life is increased, and a quality workpiece is produced. Machining parameters, such as feed rate, spindle speed, lubricant and depth of cut, can influence the sub surface damage.[12] Optimizing these machining parameters is a crucial job for both industry and academia.

A Diamond Disc Precision Cutting Machine will be very useful for the detection of subsurface damage induced in test samples once they are machined.

The working of the Diamond Disc Precision Cutting Machine can be further improved, and the quality can further be enhanced by using stepper motors instead of the feed screw which will provide with an even more precise control over the cutting plane of the machine. A precise control of the sample positioning can be crucial to studies dedicated to finding the internal integrity of a workpiece after a certain machining operation. A Stepper motor can ensure precise positioning of the workpiece over the cutting disc.

The samples are being cut with the feed of gravity or by added weights. The machine can be further equipped with a motorized feed to ensure that the cutting operation is conducted on a fixed feed rate.

Another major improvement will be to improve the coolant system. Studies have indicated that flooding a coolant over the workpiece under operation may not always produce best results. Different machining parameters on different tool-workpiece combinations may produce better results with a certain coolant provided in a certain fashion. [10]

Titanium Alloys are widely used in the industry where high strength to weight ratios are required. Applications that demand high strength materials while not providing with a flexibility to increase weight are often countered with the use of titanium-based alloys. While the titanium alloys enjoy good strength to weight ratio, their low machinability makes it difficult to produce quality product without causing damage to tool or to the workpiece.

Being deployed in the most critical of applications, the Titanium alloys are required to have minimal machining damage to avoid chances of failure hence the optimization of machining parameters is just as crucial to the Titanium based alloys.

Machining Quality is limited by the unique material properties of the Titanium metal hence by deploying the Diamond Disc cutting machine, the proper section of the machined part can be studied to identify the damage induced by the process and to optimize the machining parameters.

Needless to say, all machining procedures induce some damage to the workpiece while machining and the Diamond Disc Cutting is no different. We may find healthy literature on the Machining Studies of Titanium related to the Milling and Lathe operations. Studies indicating optimum feeds, cutting parameters, Lubricant types and quantities have been discussed however not much literature is available for the Disc Cutting operations and their damages induced on the workpieces.

This project holds a unique future prospect of providing with the opportunity to fill in the gap by studying the sub-surface damages induced by the Diamond Disc Cutting process of Titanium Based Alloys. Optimizing these parameters will allow the user to determine machining parameters that can cut samples with minimum damage to the workpiece as well as prolong the lifespan of the tool i.e., the CBN Coating of the Diamond Disc.

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