Machining Characteristics of Titanium Ti-6Al-4V, Inconel 718 and Tool Steel – A Critical Review

Mohammad Altaf1*, Shashi Prakash Dwivedi1*, Rao Shamsh Kanwar1, Imran Ahmad Siddiqui1, Pravin Sagar1, Shakil Ahmad1

1G. L. Bajaj Institute of Technology & Management, Greater Noida, Gautam Buddha Nagar, U.P. 201310, India

*Corresponding Author: spdglb@gmail.com

Abstract. Machining of hard material is always a big challenge for industrial application point of view. However, machining of this hard material is possible by taking appropriate machining parameters. Titanium Ti-6Al-4, Inconel 718 and Tool Steel are also very hard material. In this study, comparative machining study of these materials was discussed. From the exhaust literature of these materials, it was observed that machining of all these three types of hard material is possible with good surface finish by taking appropriate machining parameters.

Keywords: Titanium Ti-6Al-4V, Inconel 718, Tool Steel, Conventional Machining, Non-Conventional Machining

1. Introduction

Those materials which cannot be easily compressed, cut, bent or scratched are called hard material such as iron, glass etc. The hard material is very brittle. They have a low resistance to impact. Hard material would have high yield strength in compression. Hard material includes diamond and hardened high carbon steel. Hard material gives a poor surface finish. Due to machining of hard material the tool life reduces. There is a chance of tool breakage. Hard material resists plastic deformation. Hard material is very difficult to machine because of their ability to work harden. Hard material requires a lot of horsepower for their machining and they wear tools by both abrasion and notching. When the temperature of hard material increased it becomes very tough and plastic. Hard material increase time to produce the product. Hard material cannot maintain consistent size. Hard material cannot be rolled or cold work. Hard material has frequent tool wear, destruction, replacement.

Machining operation in which tool and workpiece have relative motion and physical contact. Turning is the machining process which is used to produce round part by single point cutting tool. Drilling is a machining process which is used to create a hole in the workpiece. Milling is a machining process in
which we remove unwanted material with the help of moulting tooth revolving cutting tool. The cutting tool is held on the spindle called arbor and the workpiece is fixed on the table.

New material having high strength and hardness such as nimonic alloy and alloy with an alloying elements such as tungsten element, molybdenum and columbium are difficult to machine by a conventional method. Due to the given reason:

- Complex shapes.
- Very high accuracy is desired besides the complexity of the surface to be machined.
- A Different form of energy directly applied to the workpiece to have shape transformation or material removal from the work surface.
- No direct physical contact between the tool and the workpiece.
- Tool forces do not increase as the work material get hard.

It was observed that by using the conventional machining to machine hard materials, there are various problems occur. To resolve these problems, the unconventional machining is used. Some benefits of unconventional machining are given below.

- EDM has the lowest specific power requirement
- ECM has highest MRR.
- USM and AJM have low material rate and combined with high tool wear.
- LBM and EBM have a high penetration rate with low MRR there for they are used for micro-drilling.
- Micro-machining and drilling – LBM and EBM.
- Cavity and standard hole drilling EDM and USM.
- Fine hole -ECM.

However, there are several disadvantages of unconventional machining. These limitations are given below.

- Expensive setup, low MRR and skilled labour required.
- The limitation of electrical machining method is that work material must be an electrical conductor. Also, the consumption of electrical energy is very large.
- The unconventional machining which has not to proceed commercially and economically are:- USM, AJM, CHM, EVM and PAM.

2. Literature Review

Peter fonda et al [1] used the EDM technologies to machine Titanium alloy Ti-6Al-4V. The important reason was to find the effect of Titanium thermal and electrical properties on EDM production. The temperature has the most important factor and there was need to find the temperature because it was essential to clarify the causes of difficulties in machining of Titanium alloy. This study showed the Titanium alloy and its properties related to the machinability. EDM is the process which is used to remove the material. There was a need to controlling the energy supplied to control the high heat generation. Temperature measure is observed for the workpiece to determine productivity and quality. The resulting temperature shows that duty factors were increased and the temperature of all body has increased. The temperature began to steady decrease which becomes the reason for poor EDM productivity. Finally, the optional duty factor in terms of productivity and quality is found around 7%.
E.O. Ezugwu et al [2] experimented to find the performance of the tools in turning of alloy of titanium (Ti-6Al-4V). Different grades of CBN tool were used. The article suggested that different grade of tool (CBN tools) gave low tool life and quality. This experiment founded important result that grade T1 was more sensitive and surface finish generated has not any adverse effect. It was also founded that with tool T1, nose wear was important failure and with tool T4 nose erosion and formation takes place. Mohammad Sima et al [3] studied various models which were used to obtain the influence of material constitutive. A method elastic viscoplastic finite element was serrated. Most materials are there which get their properties changed during the temperature changes. These were some properties which changed as strain hardening, flow softening; thermal softening and their interaction were also changed. When the machining is done with the help of orthogonal cutting process and tungsten coated carbide tool. Calculation and result were obtained by finite element simulation. Two process material flow stress and finite element formulation were not only used for chip formation but also in forces and temperature prediction. This paper has emphasized the importance of flow softening phenomenon while chip formation took place. It has been that finite element simulations are simpler if the material parameter and friction are clarified properties in the formation of the chip. Chinmaya R Dandekar et al [4] investigated through experiment to enhance the tool life and also improve the rate of material removal. In order to find the effectiveness of these two process different forces and energy were measured. Apart from this surface roughness, tool wear were also founded. In this different modeling were used to find tool wear prediction like FEM modeling. It explained that the main cost that is associated with the machining of titanium alloy is due to lower cutting speed and high tool wear. Ampara Arancharoen et al [5] has investigated in which comparison has been done between two different types of coolant used and its various possible effect on tool wear and the chip formation. This was done on titanium and one of its alloys because they are difficult to get machined. The outcomes of this experiment are noticeable as it showed resistance of tool wears increases when the developed cryogenic modular is used. It was more effective compared to oil-based coolant. It has also shown that the morphology of chip formation is different. Compared to cryogenic condition, the thicker secondary deformation zone was formed when machined under oil-based coolant condition. Kapil Gupta et al [6] analyzed every parameter in machining of the titanium alloys among the options present and choose those parameters which are sustainable. Since it is know that titanium is regarded as the material which is quite difficult to get machined, so this article provided the information about all the previous works and current works attempted for the sustainable machining of titanium alloys. This article provided knowledge about various works that have been done to improve and optimize the machining of titanium alloy. There are a lot of important factors which are considered like the effect of tool material and its geometry, advanced lubrication system, the strategy of different cooling and hybrid type machining etc. This article suggested the economic and eco-friendly ways to improve and optimize the machining of titanium alloys. Ibrahim Deiab et al [7] explained the role of lubricants in the machining of those materials which are difficult to get machined. The materials show difficulty in machining. The key point of the article is to provide a wide range of lubricants available from which sustainable alternatives can be chosen. There are various lubrication strategies explained in this article. Some of them are flooded cooling, cryogenic machining (liquid Nitrogen) and various types of lubrication combinations. This article has investigated various types of lubricant that are used during the turning of titanium alloy (Ti-6Al-4V) and its effect on roughness, tool wear and the consumption of energy for different cases. Norihiko Narutoki et al [8] described various types of tools which can be used for machining along with their different effects in the machining of titanium alloy (Ti-6Al-4V). The various tools which are discussed are- Natural diamond, Ceramic, CBN etc. It was concluded that natural diamond has the highest thermal conductivity of all materials that were present. It was also founded that natural diamond has very significant and effective cutting performance in case of titanium alloys. If the proper amount of coolant used, the result clarified that high cutting speed can be applied. The finishing of the surface was better in
case of natural diamond than any other tools available. A Pramanik et al [9] studied that increase in the MRR and increase the machining cost when temperature rise and the machining properties reduce such as strength, hardness and when chip formed this also happens. Coolant is used to improve the productivity of the Titanium. It is used at high pressure. Cooling at very low temperature is to be more beneficial and more efficient than the use of very high-pressure cooling process because at very low temperature the material behaves different properties. So in industries, it is used commonly at very low temperature that is cryogenic cooling. B.Dutta et al [10] have been seen the considerable advance is found in Additive manufacturing technology which leads to the high production of fully functional part with the use of titanium and its alloy. Whenever, technologies affect to other capabilities to form the hollow net structure with high accuracy. The direct form of energy types technology after the ability to increase the properties on the available part and manufacture the damaged part, but the building part are directly manufactured from the CAD data. Most of the study tells the true things such as mechanical properties of additive manufacturing material are better than machining which is done on lathe machine or tightening alloy for the explanation of the advantage of additive manufacture depends mostly on educating the formation and design society and the successful addition of these technologies in the manufacturing industry. The aerospace area, the medical industry have been the most sector where the titanium material is used commonly while the automotive industries are starting the use of additive manufacturing titanium and it gives a better result. M.V.Riberio et al [11] observed the behaviour of the object and good cutting conditions where the tool is manufactured with close suitable parameter or condition. It is possible to machining in more different condition than manufacturing limited condition. It is accepted that the most favorable condition and procedure which are generally used for another alloy belong to these condition for maximum production. The alloy of titanium material is difficult to machine because it has harder properties and it has higher mechanical resistance. However, the tests have accomplished the result very satisfactory. It can think the low amount of cutting fluid with working the titanium material is used. Alokesh Pramanik et al [12] have found the possible solution to increase the machining efficiency of titanium alloy. In this paper, the output parameter was explained related to a different aspect of the formation of chip and while the machining is done then the practical issue was faced and there are two different properties were produced while machining the titanium alloy which was saw-tooth chip formation and low thermal conductivity which comes during high temperature. Saw-tooth is responsible for thickness of the chip and chip thickness was the cause of variation in local temperature. There was the main difficulty with machining the titanium alloy to adjust the all cutting parameter and in the environment. When the temperature of machining was increased then the critical speed of cutting leads to saw-tooth chip supplied coolant and conductive tool holder passed the heat from the cutting zone. Two machines were there to improve finishing and dimensional accuracy. These machines are commonly used in industries of machining the titanium alloy. C.Ohkubu et al [13] studied about machinability of titanium and its alloy (Ti-6Al-4V). The specimen used in this experiment is with alpha case and without an alpha case. This experiment suggests that machinability depends on the machining condition. Except for type 4 gold alloys, a large amount of metal can be removed in this. This experiment shows that under the presence of the metal condition, it was founded that it was easier to cut metals like Ti-6Al-4V and CP Titanium. Shuting Lei et al [14] had explained the tool which is rotating and the machining of this tool occur at higher speed. The one observation that was obtained during this experiment increased the tool life. One thing was also seen that tool life in this experiment was increased approximately sixty times the normal value of the tool life. Tool life is an important factor in any kind of machining operation. Ahmet Has Calik et al [15] showed various results which are related to testing the cemented tool with titanium. Titanium alloy is very hard material so far machining the titanium alloy to the straight-grade cemented tools is used. The grain size plays an important role in tool wear and cutting edge strength. The cemented WC-Co tool was dissolution and gets diffused at high temperature. In this abrasion wear is also dominant.
at the flank and tool. The tool life can be increased by flank wear. While machining titanium the chip breaker is used. When the chip breaker is used the correct cutting parameter are determined. Kejia zhung et al [16] investigated that wear mechanism which was related to alumina based ceramic tool during the dry machining of the Inconel 718 was experimentally. The main objective of the experiment was to guide the effective way to control the wear with using various parameters such as reducing the hardened layer. These were two main modes of failure of the cutting tool which was related to the flank wear and notch wear. The presence of a hardened layer beneath the side of the workpiece surface was the main reason for the notch wear of the ceramic tool. There was a new model which tells the relationship between the depth of the notch wear and the depth of the hardened layer. Presence of a critical hardened layer thickness was the cause of the notch wear. E.O. Ezugwu et al [17] machined with Inconel 718 with SiC alumina ceramic tool and the coolant is supplied at very high pressure. It was found that to life decrease as increase the current pressure speed of cutting and feed rate gives the result the notch wear. And produces high forces increasing the forces while doing operation at high coolant supplied pressure can give result reactive forces which are generated when cutting system by momentum of the coolant supply. Low surface roughness is considered when the Inconel 718 alloy is machined with ceramic tool because both are hard material which gives more chattering when the high pressure is applied then the reactive forces are generated are not much affected. Reactive forces do not affect the surface roughness as high pressure does. J.P. Coster et al [18] showed that better wear is obtained in between 45% to 65% and cutting speed should be maintained 250 m/min. While machining is done with work under high pressure and stress reached in plastic deformation so remaining some chemical element is poured in the Inconel 718 and new compound with different property is found. This compound material shows less resistance than previous material and process is done again and again and this is done by during cutting process such as diffusion, adhesion, abrasion. The effect on grain structure on the life of tool is not much more affected because the grain size does not play an important role while cutting or machining is done. Y.E. Chen et al [19] investigated the wear mechanism while drilling the Inconel 718 alloy with the help of carbide coated tool. The friction force is the most important parameter this the governing factor for failure of the tool. Wear mechanism is found in four stages. The coated layer is recovered firstly. The wear is done by various processes as flank wear and the chip falls on the edge of the cutting tools that eroded some material which causes the wear mechanism. The crack at micro level is found near the area of chip movement and allowed to crack on the subsurface. This together with crater wear is the reason for the failure of a drilled tool in the end. The cutting tool is used to mix up with micro and nano particle in the drilling of Inconel 718 alloy. The cutting fluid reduces forces and increases the tool life. E.O. Ezugwu et al [20] observed that during the machining of Inconel-718 with a special type of tool which is whisker doped ceramic too, the tool life drastically increased along with its other physical properties under a high pressure of coolant (15MPa). This article suggested that the use of 15MPa provides a better result than 20 MPa because at 15MPa notching is eliminated during the machining operation. Hence, tool life improves. The reason that at 20MPa pressure tool life decreases is erosion. Due to high-pressure lubricants and cooling action, the cutting forces on the tool decreases. The article also suggested that, due to the round shape of the insert, the surface finish was better and acceptable. Due to the increase in dislocation directly, the analysis of machined surface shows plastic deformation and hardening of the top layer. D.G. Thakur et al [21] related the link between different physical parameters. it showed that when using tungsten carbide during turning operation of Inconel 718, there exist a relationship between different cutting forces, temperature, etc. and the relationship with thermal loading, types of chip and life of the tool. The conclusion of this article suggested that there is a noticeable relationship between the cutting parameters and the length of tool chip contact, thermal loading and chip structure. In the experiment, the result suggested that if the selection of cutting parameters and temperature is controlled then tool life can be increased by a good amount. This article has also provided us with information that the proper selection of different cutting parameters,
coolant and other important things, tool life can be increased. M.Rahman et al [22] elaborated the importance the effect of various cutting conditions on the machining of Inconel-718. In the experiment, the whole machining is carried out in CNC lathe. We founded that the performance indicator of tool life depends upon three important things, which are flank wear, surface roughness of the work piece and different cutting forces. In experiment, two different types of inserts made of cemented carbide were used. At a constant depth of cut, various cutting speed and feed rates along with side cutting edge angle are used, which played an important role to examine the tool life. Abdullah Kurt et al [23] machined Inconel-718 in order to see the importance of feed rate. These experiments indicated the important role of feed rate in machining of hard to machine materials like Inconel-718. The feed rate is connected with the stresses developed in the cutting tools. The forces are measured by series of experiments and the stresses were determined by finite element analysis (FEM). The conclusion came out that the cutting tool stress highly depends upon the feed rate used in machining. Vincenzo tebaldo et al [24] studied the effect of alternative lubrication and cutting fluid on the tool life, surface roughness and cost of the machining of Inconel 718. The economic analysis was also taken with the objective of the taking the most convenient condition. Abrasion and diffusion were the main wear. MQC which is eco-friendly system allows obtaining a tool life similar to other condition such as wet condition. MQC is the best system which gives economical cost and gives good environmental impact but when the prototype of the system was used in cryogenic refrigeration then it gives significant reduction in tool life which comes from the generated cracks and it was seen when coolant was used the poor surface roughness is obtained. With the use of cutting fluid, the production rate slightly decreases but it helps in passing the generated heat. D.M.D. Addona et al [25] had performed machining Inconel 718 at higher values of speed. During the machining of Inconel 718, the machining operation that is called turning operation was carried at the different speed occurred between low speed to high speed. In this experiment the main result obtained that was at a different speed that occurs from lower and higher speed is the gives better surface finish quality. A. Devillez et al [26] have mainly concentrated on the dry machining. During this experiment, it was found higher value of stresses that is tensile in nature, this result was obtained because of the higher mechanical property of the Inconel 718. Jinming Zhou et al [27] focused on surface roughness through experiment and also founded the surface damage and layer of surface on machining of age-hardened Inconel-718. This experiment concluded that coated CBN tool produces higher surface roughness than the uncoated CBN tool at a lower feed. The carbide is broken mainly due to high mechanical load. In terms of micro hardness, due to plastic deformation during machining near subsurface, a small difference is created. S.S. Bosheh et al [28] had been seen the plastic deformation helps in the white layer formation. The surface temperature is very essential to find the white layer. It is believed that white layer formed in cutting test. But as speed increases, the depth of the white layer decreases and it can be reduced to decrease the temperature. When the bulk material is to be machined then its hardness decreases gradually. At high speed, the temperature increase and at high-temperature gases react to the surface. The white layer is explained by vanadium density which is unaffected at high temperature. In every sector, it has been seen that white layer formation is done using CBN tool. Jeffrey D. Thiele et al [29] determined the effect on the surface roughness of tool geometry. The cutting edge of the tool and hardness of the workpiece significantly effect on the surface roughness and the cause of generating the cutting forces of hard turning of AISI S2100 steel. The study has shown that the cutting tool geometry mainly affects the surface roughness and cause the generation of cutting forces. C.H.Che Haron et al [30] had described the characteristics of the carbide tool wear eg-coated carbide tool and uncoated carbide tool based on flank wear data, which was used during the experiment. In this founded that when compression was done for the coated and uncoated carbide tool. For the coated carbide tool the wear present at the other than nose region and the range of the wear was founded to be 0.4 to 0.7 mm to the cutting edge. V.N. Gaitonde et al [31] had explained in this when machining of a material takes place material should be removed in the
one cut rather than more than one cut, which will affect the economy of the manufacturing environment. It was founded the certain value of feed force was highly valuable to feed at the different value of cutting speed and also the different value of machining time interval. The particular value of cutting force abruptly increases together with the machining time. M.A. Shalaby et al [32] conducted an experimental investigation of turning of high carbon chromium tool steel and founded how the wear mechanism of different tool material happens. There are three different materials used, some of them are- PCBN (Polycrystalline Cubic Boron Nitride), mixed Aluminium ceramic, etc. The material used for turning operation is tool steel(hardened). It showed that the chemical reaction on the surface of ceramic tool forms a layer of chromium oxide. It improved the lubricating properties due to interaction between two constituents which are work piece and environment. The results from this experiment claimed that tool of mixed alumina ceramic can perform various tasks under different machining conditions. Tzeng Yih Fong et al [33] dealt with the optimization of the multi-objective process in the machining process of multi pass lathe operations. This article explained how turning in CNC lathe can be optimized using two important techniques which are Taguchi method and PCA. In this article, the main focus is on surface roughness of product, dimensional tolerance of product and the accuracy with which it is done on machined material. There were 8 control factors investigated using Taguchi Method. Some of them are- coolant, feed, coating type, nose radius, etc. According to the PCA of the experimental results, the optimal solutions show best results in dimensional precision, accuracy and surface roughness. The optimized solution from the investigation can be used in part program in the CNC lathe. Mohammad Usman et al [34] used HIS tool with hard material increases the high temperature (2000 degree). Temperature is the most factor of the materials. Materials properties change with the increased temperature and all type of wear done more during hard turning tool wear is more. As the tool wear is more than cutting forces and cutting temperature increases with the experiment. From finite element modeling, the temperature analysis is carried out which is used by tooltip. By heat partition model the total amount of heat is calculated. In the CBN tool, the temperature is around 1500 degree. This justifies the tool wear was due to decrease in hot hardness because at high temperature the wear is more. The tool wear largely depends upon cutting temperature since the tool hardening is very effective at high temperature.

3. Conclusions

In the present study, machining review of Titanium Ti-6Al-4V, Inconel 718 and Tool Steel was carried out. From the literature review, it can be concluded that by taking the optimum combination of machining parameters in conventional or non-conventional machining, smooth surface with better MRR can be obtained. However, some difficulties were also observed during the machining of these hard materials.

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