Evaluating the grinding ratio and surface quality of Ti-6Al-4V under varying grinding pass count and depth of cut

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Abstract. Surface finishing of advanced difficult-to-machine materials through grinding is posing a significant challenge to the manufacturing industries. However, one of these materials, Ti-6Al-4V has a significantly high usage in several cutting-edge sectors. Thus, finding optimum grinding conditions for processing of this material becomes critical. Present article represents an experimental investigation dedicated towards analysing the effects of varying grinding pass counts and infeed values on the surface roughness, hardness, visible surface burns and grinding ratio of Ti-6Al-4V applying alumina wheel. Experiments are performed to reveal the trend of the surface properties and hardness of Ti-6Al-4V, ground at 10 μm and 20 μm infeed values with different sets of grinding passes. The results indicate that grinding at 15 pass count under 10 μm and 20 μm infeed values are the ideal set of parameters for the operating ranges considered herein.

Keywords: Grindability, Ti-6Al-4V, Alumina Wheel, Dry grinding

1. Introduction

Grinding is widely used to obtain surface finishes with good accuracy and close tolerances. Abrasive particles, known as grits, are bonded together to form a wheel with specified diameter and shape that eventually is used as the cutting tool in this process. Multiple cutting edges are formed from the exposed abrasive grits, which subsequently be used to remove the material in form of tiny chips. The way in which tiny chips are removed from the surface, makes the grinding process popular in respect of achieving high precision and close tolerances. Grinding can produce a surface, ten times superior than turning and milling [1]. Moreover, grinding exhibits better performances compared to regular machining processes on hard materials, in obtaining finished surfaces with desired accuracy and tolerances due to the fact that it has the ability to remove extremely thin layer of material from the surface. Nevertheless, grinding is also applied to remove large volume of material quite rapidly in some specific cases.

Grinding is a complex process as large number of randomly oriented undefined cutting edges with negative rake angle involve during the operation [2]. This results in high specific energy consumption...
During the process, which subsequently generates enormous amount of heat at the machining zone as rubbing and ploughing also take place in addition to the shearing phenomena. This excessive and highly concentrated heat affects the grinding process adversely by increasing the grinding zone temperature that results in generation of surface damages like burns, residual stresses, chip deposition, material pull-out, etc. The adversities intensify during grinding of super alloy, Ti-6Al-4V due to its inherent metallurgical properties like low thermal conductivity, low modulus of elasticity and high chemical affinity at an elevated temperature. Nevertheless, Ti-6Al-4V is an important alloy of titanium due to its unique behaviour and mechanical properties, the components of which need surface finishing with high accuracy and close tolerances as per their applications are concerned. The unique properties exhibited by Ti-6Al-4V are as follows. It has high corrosive resistance, specially under sea water, which makes it popular in shipping industry. Moreover, it possesses high specific strength and high fracture resistance which make it suitable for aerospace industry. It is 50% lighter and 30% stronger than mild steel [4]. It can also retain its high strength at an elevated temperature that makes it suitable to use in piston ring, combustion chambers, turbine blades and many more places where high temperature is maintained [3]. It is biocompatible; hence, it is used in medical science widely. The other fields, where Ti-6Al-4V is used extensively are petrochemical, chemical and nuclear industries.

During grinding, the generated heat from the machining zone is transmitted through cutting tool, i.e., grinding wheel, work piece material and via fast flowing grinding chips. However, Ti–6Al–4V is bad thermal conductive material; hence, very less amount of heat is transmitted through workpiece and via fast flowing chips, which are also tiny in sizes that results in low heat capacity. This makes grinding of Ti-6Al-4V extremely challenging as much heat will be accumulated in the grinding zone, which subsequently will increase the grinding zone temperature rapidly, resulting in escalation of adversities during the process. Additionally, Ti-6Al-4V chips tend to adhere in between the grit spaces due to their chemical affinity at elevated pressure and local temperature. This accelerates wheel-loading phenomena, resulting in faster wheel wear rate, which subsequently affects the product quality adversely [5]. To deal with these challenges, operators are forced to maintain benign grinding parameters, unless special measures are taken, resulting in lower rates of material removal [6]. Apart from the adoptions of proper grinding measures like optimization of dressing techniques [7-10] and process parameters [11-12], application of economic and environment-friendly coolants [13-14] using effective delivery techniques [15] etc. need to be undertaken.

Due to the difficulties faced during conventional grinding of Ti-6Al-4V, many measures have been experimented and adopted to eradicate these issues. In this report, an effort has been made to study the changes in the hardness, roughness and grinding ratio of Ti-6Al-4V under varying depth of cut and number of passes.

2. Materials and Methods
Experiments are performed on a horizontal surface grinding machine. Rectangular Ti-6Al-4V plates of size 30 mm × 19 mm × 6 mm and hardness 33 HRC are conceived for the present set of experimentations. Identical aluminium oxide wheels have been employed for the different set of experiments. The details of materials and adopted methodologies are depicted in Table 1. Two different infeed values, 10 μm and 20 μm are applied while grinding has been performed under five different number of passes viz. 5, 10, 15, 20 and 25. The parameters were selected in order to realize the effect of propagation of grinding process for different infeed values. Each pass is comprised of both up-feed and down-feed, and infeed was given twice every pass.

Alumina wheel has been trued before the starting of the experimentations followed by workpiece truing, wheel dressing and sparking out process. The wheel has been dressed after every set of passes with the help of a 0.75 carat diamond at 20 μm infeed, which is the optimized dressing infeed for conventional wheel [9-10]. Constant wheel speed of 2800 rpm has been maintained throughout the experiment. The height of the workpiece has been measured before and after every set of pass count with a vernier...
calliper. The hardness of the workpieces is measured by a Rockwell cum Brinell hardness tester and the roughness was measured by a Talysurf roughness tester. Bulk hardness testing of the work material was performed on the ground surface to analyse and detect the presence of work hardening during the grinding process. The grinding process is shown in Figure 1.

**Table 1.** Details of experimentation.

| Parameter                        | Details                                                                 |
|----------------------------------|-------------------------------------------------------------------------|
| Surface Grinding Machine         | Make: Bhavya M/C Tools  
                                   | Model: BSG-225  
                                   | Infeed Resolution: 10 μm  
                                   | Motor Power: 1.5 kW  
                                   | Spindle Speed in No-load Condition: 2800 rpm |
| Grinding Environment             | Dry                                                                      |
| Work Piece Material              | Material: Ti-6Al-4V;  
                                   | Composition (by volume): Titanium - 88.77%; Vanadium - 4.25%; Aluminium - 6.19%; Iron - 0.34% |
| Grinding Wheel                   | Alumina:  
                                   | Specification - AA60K5V8  
                                   | Make - Carborundum Universal Ltd.;  
                                   | Dimensions - Φ 200 mm × 31.75 mm × 13 mm |
| Rockwell and Brinell Hardness    | Make: Blue Star Limited  
                                   | Model: BSHT-250FRB  
                                   | Load: 60-250 kgf |
| Wheel Dresser                    | 0.75 carat Single Point Diamond |

**Figure 1.** Pictorial view of grinding setup.
3. Results and discussion
Among the several parameters for assessment of grindability of a material work hardening, average surface roughness, surface quality and volume of work material removal are some significant factors. Figure 2 represents the variations of hardness of Ti-6Al-4V, before and after grinding, with the number of pass counts at various infeed values. It can be observed that the hardness of Ti-6Al-4V decreases after grinding, which can be attributed to the work softening that occurs due to air cooling in dry grinding processes. The effect of annealing with air cooling is significantly distinguishable that leads to work softening.

![Figure 2](image)

**Figure 2.** Work material hardness, measured before and after grinding under varying infeed values.

![Figure 3](image)

**Figure 3.** Average surface roughness values for different grinding passes under varying infeed values.
Figure 3 illustrates the variations in average roughness (Ra) for Ti-6Al-4V with the number of pass counts at different infeed values. The roughness values have been found to be increased with the increase in number of pass counts as expected. However, for 10 µm depth of cut, the average surface roughness values are found to be lower during 15 and 20 passes. This may be due to the excess wheel loading followed by rubbing and glazing during those pass counts.

Figures 4 and 5 depict the Ti-6Al-4V ground surfaces at various infeed values and pass counts. From these figures it is clear that the surface has burns and presence of chip redeposition. Grinding for 15 pass count at both 10 and 20 µm infeed values exhibit better parameters because the roughness values and burns on the surface are found to be significantly lesser.

During grinding, it is expected to have more workpiece material removal and minimum wheel wear. The performance can be estimated by considering the ratio between this two i.e., the volume of workpiece material removal and volume of wheel wear. This ratio known as grinding ratio is also called G ratio. This is an important parameter to evaluate grindability of a given material, which is defined as the ease of grinding. The volume of workpiece material removal is calculated at the end of each set of pass counts with the measurement of the change in height of workpiece as showed in figure 6. From this figure, it is evident that material removal is increased when infeed values and number of pass counts are increased.
4. Conclusions

In this experimental investigation, grinding of Ti-6Al-4V has been performed using aluminium oxide wheel. Effects of varying infeed values and number of grinding pass on surface properties like hardness, roughness, visible burns and also on the grinding ratio have been extensively studied. Following major inferences can be extracted from the current analysis.

- The work softening due to air cooling during grinding of Ti-6Al-4V results in decrease in the hardness.
- The surface roughness values have increased as expected when the infeed values have been increased.
- The G ratio enhances in case when both infeed values and number of passes are increased.
- Considering all the observations of the present study, it can be inferred that grinding under 15 pass count at 10 and 20 μm depth of cut are the ideal set of parameters for the operating ranges considered herein.

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