

Investigation of High-Speed Milling and High Efficiency Milling of Ti6Al4V

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Keywords— *Spacecraft, High-Speed Milling, High Efficiency Milling, Ti6Al4V, Machining.*

Abstract— *Ti6Al4V a Titanium alloy, is one of the prominent materials used in spacecraft components and it is a difficult to machine material. In this paper and experimental investigation is carried out to compare High Efficiency Milling (HEM) and High-Speed Milling (HSM) of Ti6Al4V. The MRR, surface roughness and tool wear were determined from the investigation. From the work it was found out that the MRR for HEM was less than that of HSM, while surface roughness variation was less and no significant tool wear was observed for HEM strategy.*

I. INTRODUCTION

Titanium alloys constitute one of the most important materials in spacecraft because of its high specific strength and good corrosion resistance. Several spacecraft mechanism components are made of Titanium alloy Ti6Al4V. As machining is the most apt manufacturing strategy in realizing the spacecraft titanium parts, owing to the high dimensional and geometric tolerances called for, it is majorly used for the realization of the parts. Of various machining operations, major bulk of the workpiece material is removed using milling operations.

As Titanium is very difficult to machine material due to its low thermal conductivity and chemical reactivity, only limited cutting tool materials can be used. Also due to the poor machinability, cutting tools experience tool wear leading to reduced tool life. Hence, it calls for exploration of advanced machining technologies like High Speed & High Efficiency Machining etc.

II. HIGH SPEED MACHINING

King, R. I (1985) discussed the history of High Speed Machining initially proposed by Salomon and its relevance

to aircraft structures made of Aluminium. Ippolito, R et al. (1988) conducted the High-Speed turning tests for steel with ceramic tool to study the effects of machining parameters on surface finish, tool life, chip formation. Schulz, H., & Moriwaki, T. (1992) reviewed the key developments in high-speed machining and related fields like cutting tools and machine tools and mentioned more than fifty percent reduction in time is achievable. High-speed machining of Aluminium aircraft structures, titanium fan blades and hardened steel dies was presented in Tlustý, J. (1993) along with high-speed grinding of gears. Dagiloke et al. (1995) developed a software package which allows user to obtain process parameters for changing cutting conditions in both conventional and high-speed regimes. The advances in high-speed machining called for the development of associated machine tools and kinematics. (Heisel, U., & Gringel, M. (1996)). Dewes, R. C., & Aspinwall, D. K. (1997) investigated the aspects of tool life, workpiece surface finish, dimensional accuracy and cost for machinability through high-speed machining. The selection of the right tool path for high-speed machining of thin, flexible webs in Aluminium parts is discussed in Smith, S., & Dvorak, D. (1998). Han, G. C et

al. (1999) developed Look Ahead Interpolation algorithm to obtain the smooth continuous motion of each axis of CNC machine tool and verified through experiments, on machine tools. The results showed an increase in machining speed. Urbanski, J. P et al. (2000) conducted an experiment to machine the hardened AISI H13 hot work tool steel in HSM regime, using indexable insert ball nose end mills. Tool life of different tool inserts and factors affecting them were investigated and the effect of different inserts on surface roughness values and cutting forces were also studied. Compressed chilly-air coolant was found to increase the tool life. Lei, S., & Liu, W. (2002) developed a new generation of driven rotary lathe tool for high-speed machining of Ti-6Al-4V and conducted experiments for cylindrical turning. When compared with the stationary tool, results showed an increase in tool life for the driven rotary tool. de Lacalle, L et al., (2004) studied the effects of tool deflection on the dimensional errors in the high-speed machining of hardened steel surfaces. They conducted the tests by applying different machining strategies. Their work explored the various practical problems encountered and to be resolved to achieve stringent dimensional accuracies. The tool wear, size of burr and machined surface quality were studied. Rahman, M et al. (2006) presented an overview of developments in the field of high-speed machining of Titanium alloys, geometric modelling and cutting force models for high-speed machining of Titanium alloys. They have also proposed a hybrid cutting force model, based on FEM simulation and Oxley's machining theory, and this model was found to predict the cutting forces accurately. Su, Y et al. (2006) performed high-speed machining of Titanium alloy Ti-6Al-4V under dry, flood coolant, nitrogen oil mist, Compressed Cold Nitrogen Gas (CCNG) and Compressed Cold Nitrogen Gas and Oil Mist (CCNGOM), using coated cemented carbide tools. Results showed that CCNGOM condition increased tool life. Ekinović, S et al. (2007) performed machining tests on different materials with different hardness, different machinability index and by using different experimental approaches. In combination with new cutting tools, common production machines can be effectively in high-speed machining applications. Their work highlighted the advantages of high-speed turn-milling over conventional machining

Study of tool wear mechanism through diffusion wear during high-speed machining is critical in assessing the tool life. Zhang, S et al. (2009) proposed the diffusion analysis of tool chip interface while high-speed milling of Ti-6Al-4V alloy with straight Tungsten Carbide tools. Diffusion was analyzed using Scanning Electron Microscope and dispersive X-Ray spectroscopy. The study showed that pulling out and removing of WC particles due

to Cobalt diffusion dominated the crater wear mechanism. Hashmi, K. H et al. (2016) developed an average surface roughness (Ra) model for milling of Ti-6Al-4V alloy using Carbide inserts tooling. Responsive Surface Methodology (RSM) is used to arrive at a relation between Ra and machining parameters. Their findings showed that the depth of cut is the most influencing parameter on surface roughness in high-speed machining range of Ti-6Al-4V while cutting speed and feed rate does not have a notable effect.

III. HIGH EFFICIENCY MACHINING

High-speed machining involves high cutting speeds and low feeds per tooth, leading to extremely short times of contact between workpiece and tool, very high frequencies of contact and high cutting temperatures [1]-[17]. The HSM calls for totally different tool design concentrating mainly on the insert type tools, wherein only the limited height of the tool is utilized for the machining. To efficiently utilize the entire tool length, new machining strategy was developed known as High Efficient Machining (HEM), which calls for different tool design, machine tool architecture and machining strategies. (WitGrzesik, 2017 & HEM Guidebook, 2017)

Tönshoff, H. K et al. (1999) explored this very idea of HEM and its variation from HSM. The work reviewed the previous work and existing practices in the aerospace industry and mentioned the requirements for HEM like high spindle power, machine structures, coolant system, cutting tool requirements, drive controls etc. The work also highlighted the advantages of HEM for aerospace components. Potentials of HEM was also presented. Chan, K et al. (2003) developed a high-efficiency 2.5 dimensional rough milling strategy for mould core machining. Their strategy consisted of three tool paths while the first two toolpaths performed a rouging operation and the third one removed the staircase pattern left out by first two tool paths. Zhao, W et al. (2004) presented an efficient approach to control the machining deflection while machining the thin-walled aerospace jobs using high-efficiency machining strategy. They performed FEM analysis and also conducted an experiment to analyze the same, on AA 2024- T351 aluminium alloy. Increase in machining precision and decrease in machining time was observed. Xu, D. M et al. (2011) developed a high-efficiency machining tool path design of die cavities. Tool path was based on the minimum numbers of rectangular or triangular patterns to cover the roughing areas. Their work compared the traditional Z-milling and plunge milling to demonstrate the higher cutting efficiency. Their cutting simulation results and experimental results showed that,

cutting efficiency of plunge roughing increased with cutting depth.

From [1]-[23] it was observed that, very limited work pertaining to comparative study of High-speed machining versus High Efficient Machining of aerospace components, has been done. Since Ti6Al4V alloy is the most commonly used Titanium alloy in spacecraft components and it is a difficult to machine material, exploration of advanced machining strategies especially milling is required. To the best of the authors knowledge and from the literature survey, no work was done to study the High Speed Milling (HSM) and High Efficiency Milling (HEM) of Ti6Al4V for spacecraft components. Hence it is proposed in this work to carry out the experimental investigation of the same for Ti6Al4V alloy.

IV. METHODOLOGY

a. Work Material

Since Titanium components are difficult to machine and they are found in various spacecraft subassemblies, Ti6Al4V alloy was selected for the experiment as it is the most widely used alloy in spacecraft components. The composition and properties of Ti6Al4V are given in Table 1 & Table 2 and HEM is carried out on Ti6Al4V. The composition and properties of Ti6Al4V are given in Table 1 & Table 2.

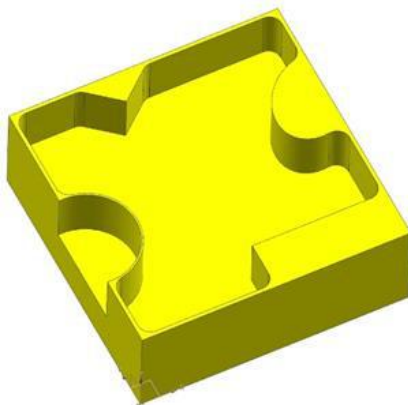


Fig 1. CAD Model of the sample

Table 1. Composition (in %) of Ti6Al4V

Al	5.5-6.5
V	3.5-4.5
Fe	0-0.3
O	0-0.2
Ti	Balance

Table 2. Properties of Ti6Al4V

Density (g/cc)	4.4
Youngs Modulus (GPa)	108
Yield Strength (MPa)	883
Melting Point ($^{\circ}\text{C}$)	1660
Thermal Conductivity (W/(m-K))	17
Linear Thermal Expansion Coefficient (10^{-6} K^{-1})	9

b. Geometry of test Part

A block of 110mm length, 110mm width and 37.5mm height was used for carrying out milling experiments. The features which are generally encountered in the spacecraft components were considered while arriving at the internal topology of the sample piece. The CAD model of the sample piece is given in Fig 1.

c. Machine tool and Cutting Tools

All experiments were conducted on DMC 650V vertical CNC Milling machine with a maximum spindle speed of 20,000 rpm. A CERATIZIT Indexable cutter with 20mm diameter with TiN-TiB₂ (Titanium Nitride - Titanium Boride Coated Inserts) were used for HSM experiment and CERATIZIT TiSiN coated solid carbide end mill cutter with 20mm diameter was specially used for HEM experiment. These tools were used mainly for roughing operations. For finishing operation 3 Flute TiN Coated Carbide End Mill cutter with 10 mm diameter was used. The details of the cutting tool are given in Fig 2.



(a)



(b)

Fig 2. Geometry of Cutting tool
(a) Milling Cutter (b) Carbide insert

d. Experimental Procedure

The experiment was conducted by performing the CNC Milling operation on the workpiece material to achieve the final component as per the CAD model in Fig 1. The toolpaths for HSM and HEM were generated in UG NX and POWERMILL software respectively. Sample toolpath for HSM is given in Fig 3.

The cutting speed range for HSM were presented in Schulz, H., &Moriwaki, T. (1992) and same were used to calculate cutting speed for the experiment. The cutting parameters employed in this investigation for HSM were listed as follows: Cutting speed $V_c=113$ m/min

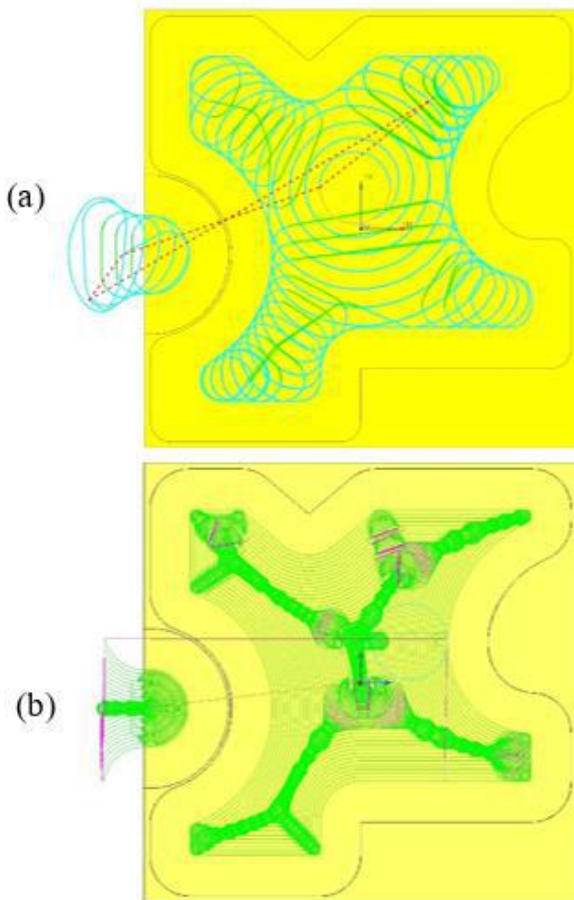


Fig 3. CAM toolpath (a) HSM (b) HEM

(correspondingly, the spindle speed N was 1800 rpm), feed $f_z=0.093$ mm/tooth (correspondingly, the feed rate for three flute cutter was 502 mm/min), axial depth of cut $a_p=0.5$ mm and radial depth of cut $a_e=6$ mm (30% of 20mm diameter cutter).

The methodology to select the cutting parameters for HEM are elucidated in [23] and same were considered for fixing the HEM cutting parameters. The cutting parameters for HEM were listed as follows: Cutting speed $V_c=25.13$

m/min (correspondingly, the spindle speed N was 400rpm), feed $f_z=0.0625$ mm/tooth (correspondingly, the feed rate for two flute cutter was 100 mm/min), axial depth of cut $a_p=20$ mm and radial depth of cut $a_e=1$ mm (5% of 20mm diameter cutter).

Before arriving at the cutting parameters several trials were done on sample workpieces and finally above mentioned cutting parameters were finalized. The milling was carried out up to 20mm depth as per CAD model.

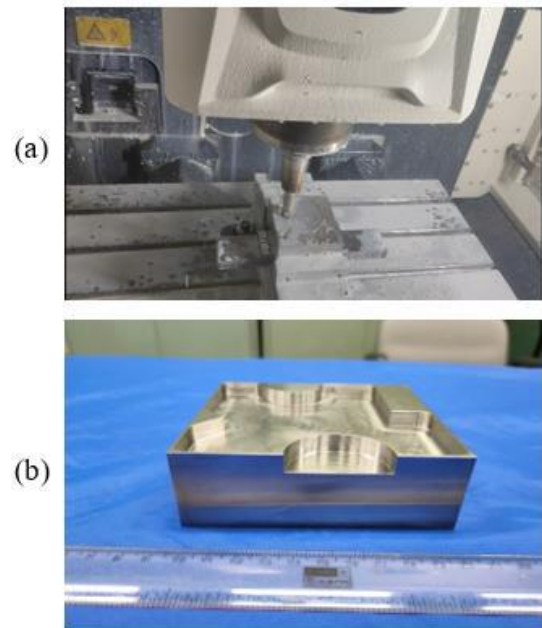


Fig 4. HSM (a) Component under machining (b) Finished Component

As the main aim of the work was to compare HSM and HEM, only one set of cutting parameters were considered for the investigation. The tool wear for both HSM and HEM were measured with LEICA-M205 microscope with magnification of around 40x, periodically to ensure that maximum crater wear does not exceed 0.3mm uniform flank wear or 0.5mm localized flank wear whichever occurs first as per the standard (ISO 8688-2:1989). Total machining time for both HSM and HEM was measured from the machine control unit display.

The milled samples were cleaned with acetone and then deburred before carrying out the actual measurements of the surface roughness. The surface roughness was measured on both wall and floor, to compare the results for both the strategies. The surface roughness measurement was done using Taylor Hobson Talysurf profilometer. While machining the spindle parameters were monitored through MCU display. The components while machining and finished pieces are given in Fig 4 and Fig 5 for HSM and HEM respectively.

V. RESULTS AND DISCUSSIONS

a. Material Removal Rate (MRR)

The MRR for actual machining operation were determined for both HSM and HEM and results of same are illustrated in Fig 6. It is inferred from the graph that, MRR for HEM is around 7% less than that of HSM. This may be because of the very less radial depth of cut, leading to longer toolpath.

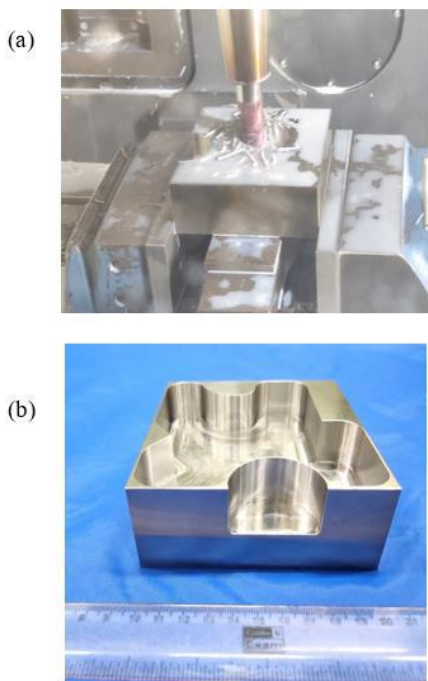


Fig 5. HEM (a) Component under machining (b) Finished Component

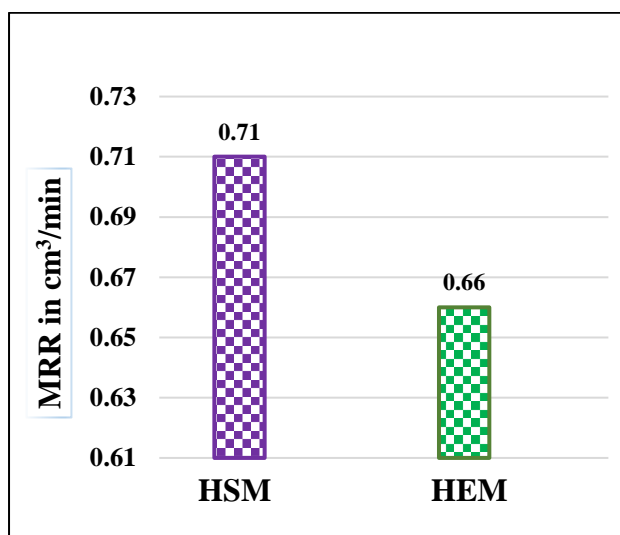


Fig 6. Material Removal Rate (MRR)

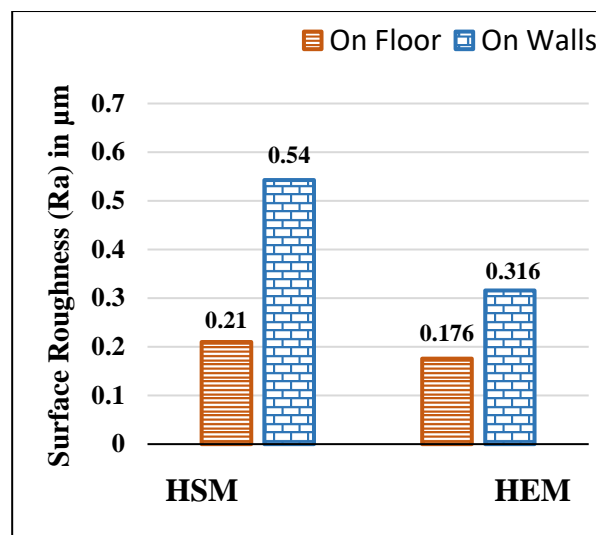


Fig 7. Surface Roughness (Ra)

b. Surface Roughness (SR)

The surface roughness was measured on both walls and floor, and maximum R_a value is reported in the work and results are given in Fig 7. From the results it was observed that SR value on floor for HEM was less than that of HSM while SR values on walls was considerably high for HSM than HEM. This may be due to gradual wear of the tool.

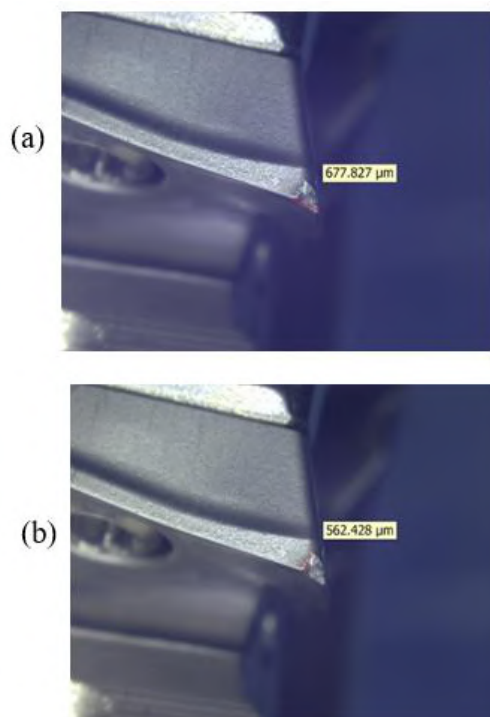


Fig 8. HSM flank tool wear

(a) Lengthwise (b) Widthwise

Tool Wear The measured tool wear (as per ISO 8688-2:1989) for both HSM and HEM strategies are presented

in Fig 8 and Fig 9 respectively. For HSM flank wear of 0.677mm on lengthwise and 0.562mm on width of the flank was observed. However, for HEM no flank wear was observed but loss of coating was observed for both length and width of flak wear. The increased axial depth of cut with less speeds and feeds compared to HSM may be the cause of coating loss on tool and absence of tool wear.

c. Chip Morphology

In HSM, the chips are shorter and curly, as the cutting edge in contact with the metal during machining is short, due to the low depth of cut. In HEM, as cutting edge of the tool is utilized to its optimum cutting length, the length of the chips is more, due to more depth of cut.

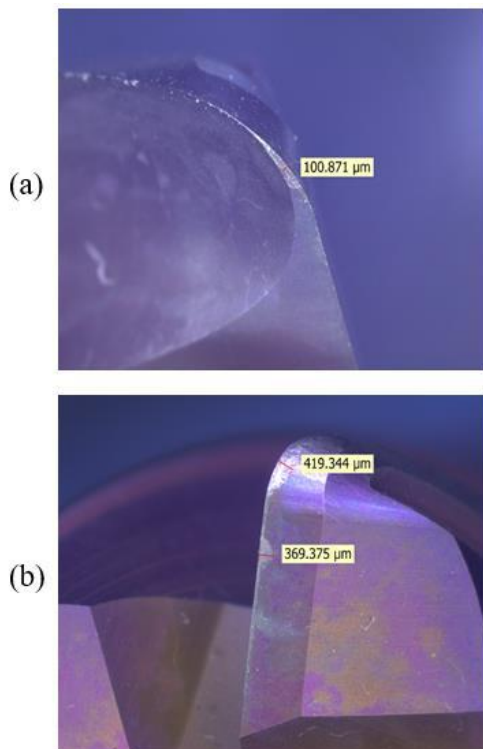


Fig 9. HEM flank tool wear
(a) Widthwise (b) Loss of coating

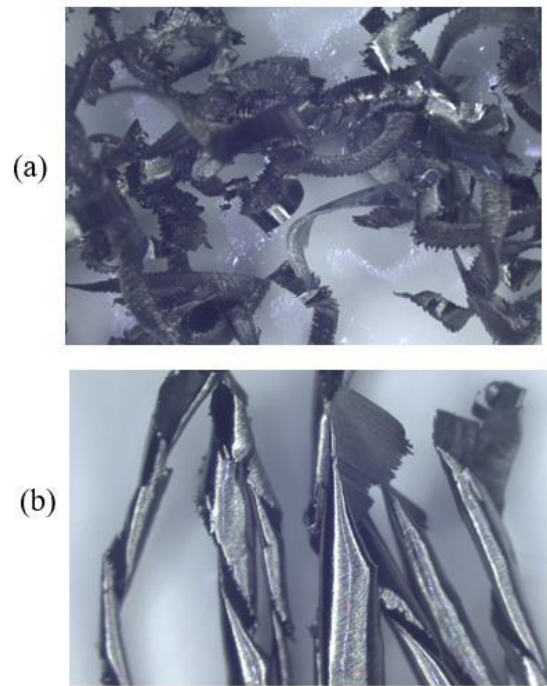


Fig 10. Chips during machining
(a) HSM (b) HEM

VI. CONCLUSION

It can be inferred from the experiment conducted that, there is slight decrease in MRR for HEM than HSM. However, HEM was instrumental in generating better surface finish and lesser tool wear compared to HSM. It can be seen that for Ti6Al4V, HEM seems to be more promising than HSM. However, owing to several factors, the trade-off between HSM and HEM while machining spacecraft components would be a suitable option, depending upon the component than choosing only one method.

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