Investigation of High-Speed Milling and High Efficiency Milling of AA6061

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Abstract**—*Milling is one of the most prominent machining processes employed in the realization of spacecraft mechanical hardware which vary in size, shape, material and complexity. In this work a study is carried out to compare High-Speed Milling (HSM) and High Efficiency Milling (HEM) of AA6061. The machining time, surface roughness and tool wear were determined from the investigation. From the work it was found out that the lesser machining time with better surface finish was observed while machining by HSM than that of HEM and very negligible tool wear noticed.***

Keywords**—*Spacecraft, High-Speed Milling, High Efficiency Milling, AA6061, Machining.***

I. INTRODUCTION

Spacecraft consists of several mechanical hardware which vary in materials, size, shapes, complexity etc. Stringent dimensional and geometric tolerances, and quantity restricts the realization mainly to only machining process, that too majorly milling process. Adhering to the tight launch schedules is also one of the prime requirements. Hence trade-off between quality and delivery schedule is crucial in the realization of spacecraft mechanical hardware and meeting the project schedules. In this view, exploration of advanced technologies is very crucial. Aluminium alloys constitute major part of these spacecraft hardware due to the various advantages like light weight, strength, easy machinability, corrosion resistance etc., and among various aluminium alloys, AA 6061 is most widely used for spacecraft mechanical hardware.

II. HIGH SPEED MACHINING

The history of High-Speed Machining was discussed in *King, R. I (1985)* and it was mentioned that modern aircraft structures built of Aluminium were required to be made in one piece to achieve structural integrity. Hence, idea of high-speed machining was developed in order to reduce the machining time for removing bulk of solid material. High Speed turning tests conducted for steel with ceramic tool was reported in *Ippolito, R et al. (1988)*. Effects of machining parameters on surface finish, tool life, chip formation etc were investigated and their significance was assessed. *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 *Tlusty, J. (1993)* along with high-speed grinding of gears. 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 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 the increase in machining speed. When compared with the stationary tool, results showed increase in tool life for 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. Ng, E. G et al. (2004) carried out an experiment and analysis of high-speed machining of Aluminium alloys A356-T6 for automotive applications. The tool wear, size of burr and machined surface quality were studied. Kazban, R. V et al.(2008) measured the temperature and force fields in high-speed machining of Aluminium alloy 6061-T6. They modified experimental orthogonal machining Hopkinson bar apparatus to conduct an experiment. Study showed that wear land significantly contributes to the heating of the workpiece land and is significant mechanism for residual stresses and temperature rise on finished surface.

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]-[12]. The High Speed Machining calls for totally different tool design concentrating mainly on the insert type tools, where in only 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 Efficiency Machining, which calls for different tool design, machine tool architecture and machining strategies. (WitGrzesik, 2017 &High Efficiency Machining Guidebook, 2017)

Tönshoff, H. K et al.(1999) explored this very idea of High Efficiency Machining and its variation from High Speed Machining. The work reviewed the previous work and existing practices in the aerospace industry, and mentioned the requirements for High Efficiency Machining like high spindle power, machine structures, coolant system, cutting tool requirements, drive controls etc. The work also highlighted the advantages of High Efficiency Machining for aerospace components. Potentials of High Efficiency Machining 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 first two toolpaths performed rouging operation and third one removed the staircase pattern left out by first tow tool paths. Zhao, W et al.(2004) presented an efficiency approaches 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 were 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]-[18] it was observed that, very limited work related to comparative study of High-speed machining versus High Efficiency Machining of aerospace components has been done. As various spacecraft mechanical hardware are fabricated using milling operation, it is proposed to investigate High Speed Milling (HSM) and High Efficiency Milling (HEM) and to the best of the authors' knowledge and literature survey, where no work was reported in the field of application of HEM to spacecraft materials. Hence, in this work it is proposed to investigate the HSM and HEM of AA 6061, and the best strategy which reduces the machining time and increases the dimensional stability.

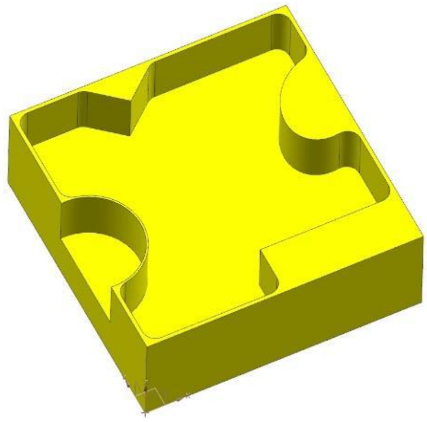

Fig 1. CAD Model of the sample

IV. METHODOLOGY

a. Work Material

Since majority of the spacecraft mechanical hardware are comprised of Aluminium alloys especially AA6061, investigation of HSM and HEM is carried out on AA6061. The composition and properties of AA6061 are given in Table 1 & Table 2.

Table 1. Composition (in %) of AA6061

Al	95.85-98.56
Mg	0.8-1.2
Si	0.4-0.8
Fe	0-0.7
Cu	0.15-0.4
Zn	0-0.25
Ti	0-0.25
Mn	0-0.15

Table 2. Properties of AA6061

Density (g/cc)	2.7
Youngs Modulus (GPa)	68.67
Yield Strength (MPa)	276
Melting Point (^{0}C)	660
Thermal Conductivity (W/(m-K))	167
Linear Thermal Expansion Coefficient (10^{-6} K^{-1})	23

b. Geometry of test Part

A square 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 DMU 650V vertical CNC Milling machine with a maximum spindle speed of 20000 rpm. A CERATIZIT insert based indexable cutter with 20mm diameter were used for HSM experiment and CERATIZIT 20 mm solid carbide end mill cutter was used for HEM experiment. For corner finishing operation 3 Flute TiN Coated Carbide End Mill cutter with 10 mm diameter was used. The details of the cutting tool are shown in Fig 2.

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. The toolpaths for HSM and HEM are given in Fig 3.

(a)

(b)

Fig 2. Geometry of Cutting tool

(a) Milling Cutter (b) Carbide insert

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=1225 m/min (correspondingly, the spindle speed N was 195000 rpm), feed f_z=0.11mm/tooth (correspondingly, the feed rate for three flute cutter was 6435 mm/min), axial depth of cut a_p=0.5mm 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 [18] and same were considered for fixing the HEM cutting parameters. The cutting parameters for HEM were listed as follows: Cutting speed v_c=251 m/min (correspondingly, the spindle speed N was 4000 rpm), feed f_z=0.1mm/tooth (correspondingly, the feed rate for two flute cutter was 800 mm/min), axial depth of cut a_p=20 mm and radial depth of cut a_e=2mm (10% of 20mm diameter cutter).

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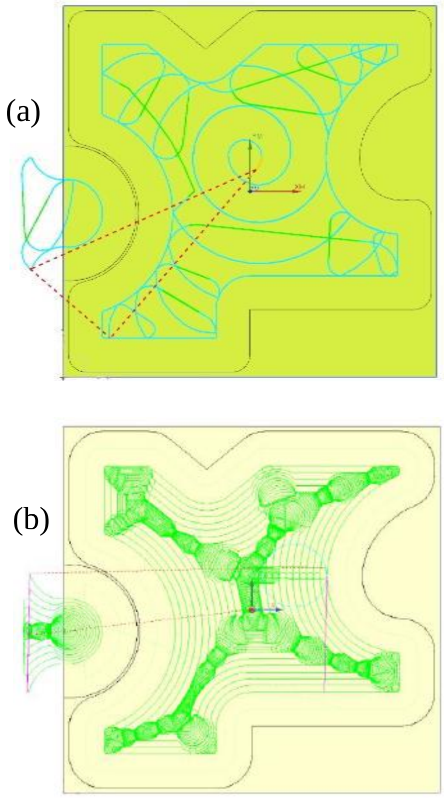

Fig 3. CAM toolpath (a) HSM (b) HEM

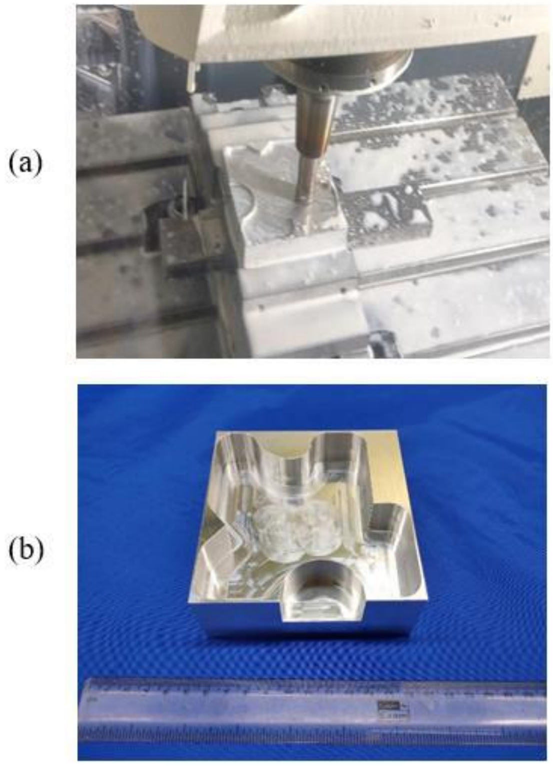

Fig 4. HSM (a) Component under machining (b) Finished Component

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 upto 20mm depth as per CAD model

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 degreased 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.

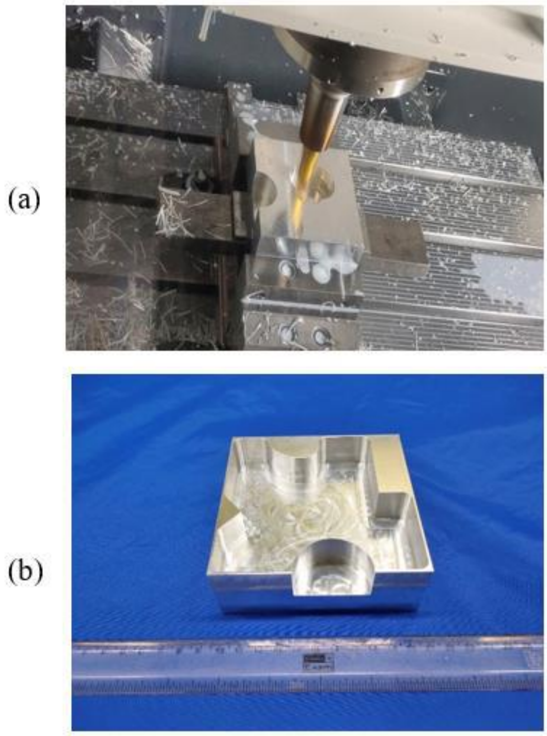

Fig 5. HEM (a) Component under machining (b) Finished Component

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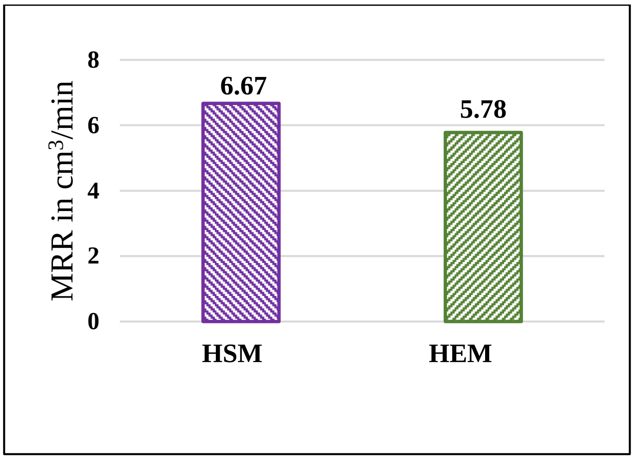


Fig 6. Material Removal Rate (MRR)

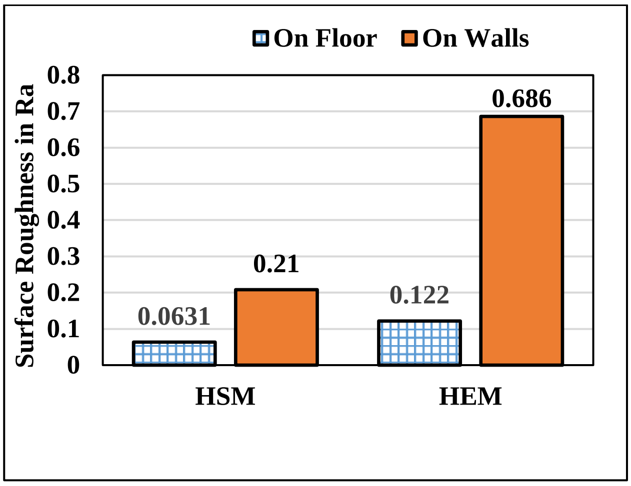


Fig 7. Surface Roughness (Ra)

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 HSM is around 13.34 % more than HEM and is due high speed and feed rate.

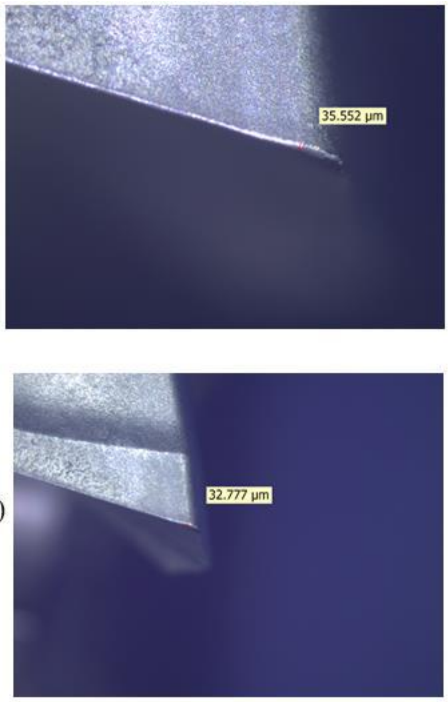
b. Surface Roughness (SR)

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 HSM was less than that of HEM while SR values on walls was considerably high for HEM than HSM. This may be attributed to the high a_p for HEM.

c. 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 of AA6061 very negligible flank wear of 35.5 microns on lengthwise and 32.8 microns on width wise was observed. However, for HEM no flank wear was observed but loss of coating was observed for both lengthwise and width wise. The increased axial depth of cut with less speeds and feeds compared to HSM may be the cause of loss of coating on tool.

(a)

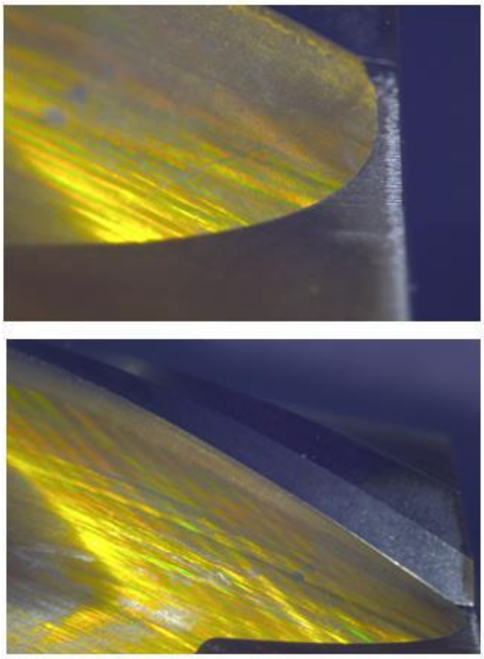


(b)

Fig 8. HSM flank tool wear

(a) Lengthwise (b) Widthwise

(a)



(b)

Fig 9. HEM flank tool wear

(a) Widthwise (b) Loss of coating

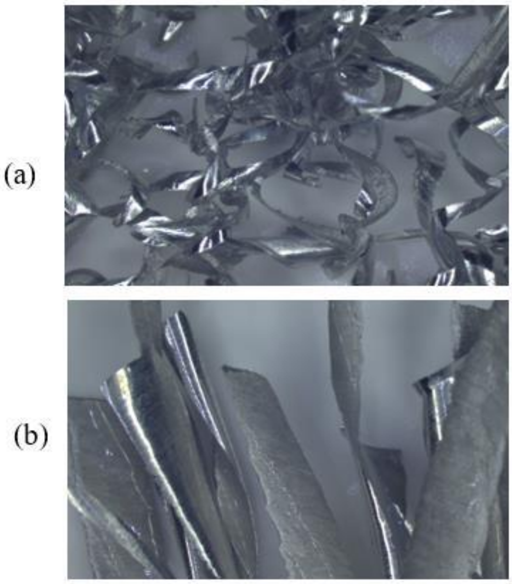


Fig 10. Chips during machining

(a) HSM(b) HEM

d. Chip Morphology

In HSM, the chips are continuous but shorter in length, 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 maximum optimistic length, the length of the chips is more.

VI. CONCLUSION

From the investigation, it was observed that HSM and HEM are equally capable of reducing the machining time when compared to the non-HSM regime. HSM consumes less machining time than HEM. Moreover, Surface finish on both the floor and wall were found to be better than that one done with HEM.Tool wear is not present in HEM except for loss of coating whereas negligible flank wear is present in HSM. Owing to all these, while machining of spacecraft components, selection of proper machining methodi,e HSM or HEM or combinations of these machining methods are needed to meet the requirements.

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