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# Characterization of thrust performance of micro-nozzle machined by micro-end milling

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**Abstract**

Micro thruster is the power plant of mini-spacecraft. It enables the mini-spacecraft to realize orbit adjustment, station keeping and attitude controlling. Micro nozzle is one of key parts of the micro thruster. The surface roughness of its inner surface significantly influences the thrust performance of the thruster. In this paper, a residual surface model is developed for micro-nozzle obtained by micro machining using a ball end mill and a taper end mill. The residual surface model is then used to investigate the relationship between the surface quality and nozzle thrust performance in nozzle flow field. A thrust measuring apparatus is designed and manufactured to inspect the thrust performance of the machined micro nozzles. Both simulation and experiment results indicate that good machined surface quality is obtained with taper end mill. The nozzle machined with the taper end mill has better thrust performance than that with the ball end mill under the same inlet pressure.

Key Words: Micro nozzle; Micro machining; End mill; Thrust performance

## 1. Introduction

Micro thruster has been presented itself as an important role in space missions. In a thruster, the Laval nozzle is primarily used to increase the outlet velocity. It is rather necessary to increase efficiency as higher effective outlet velocity could generate more thrust with the same mass flow [1]. As a key part of micro thruster, micro Laval nozzle determines the performance of the thruster.

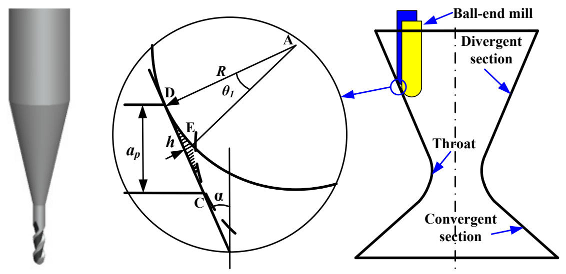
Performances of micro nozzles are significantly influenced by machined surface roughness with micro-cutting technology. Especially, distinguished difference between micro nozzle and conventional scale nozzle lies in the fields of fluid properties and manufacturing difficulty. With the nozzle scale reducing, the combination effects of viscous/rarefaction on the micro-scale significantly influence the flow behavior in micro-nozzles [2]. Besides, roughness effect and boundary layer thickness are also distincted for micro nozzle from normal scale nozzle [3]. The roughness of the nozzle inner surface should be minimal as roughness effects lead to boundary layer, flow separation and shock formation in the nozzle, which degrades the performance of the nozzle [4].

This research focuses on roughness effect on nozzle thrust performance. Firstly, a residual surface model based on two different tool types was built. Then, CFD simulation of micro nozzle was investigated. Finally, actual thrusts of different nozzles were tested.

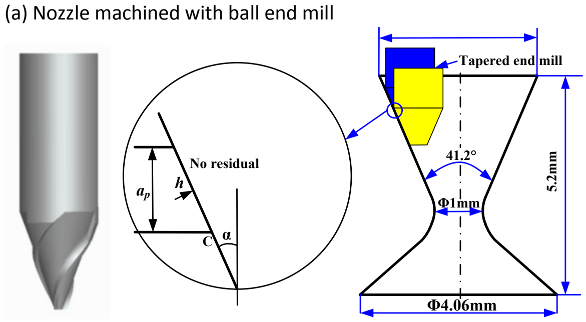
## 2. Residual surface model

Residual surface model based on geometry condition was shown in Figure 1. In machining process with the ball-end mill, optimization of cutting parameters can partly improve surface quality, but at the expense of efficiency. In this research, taper end mill is applied for nozzle finish machining. Ball end mill is one commercial standard milling cutter in nozzle machining process, but the applied taper end mill is a non-standard tool, which is designed adapting to the taper angel of micro nozzle to be machined.

The micro nozzle with throat diameter of 1mm was chosen as the case study. Nozzle dimensions are illustrated in Figure 1(b). Residual surface model is utilized in nozzle simulation, as illustrated in Fig. 1, to represent the actual machining surface topography.



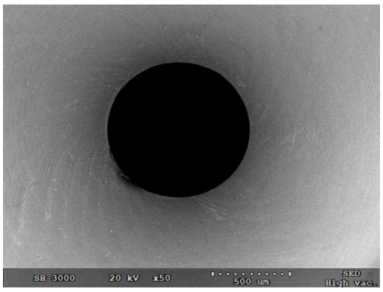

(a) Nozzle machined with ball end mill



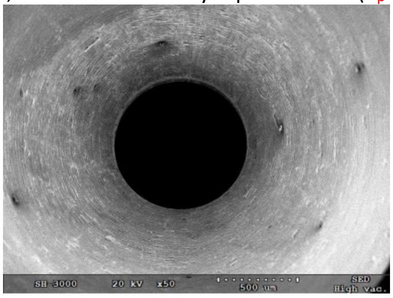

(b) Nozzle machined with taper end mill

**Figure 1.** Diagram of residue surface machined by ball end mill and taper end mill

As shown in Figure 1, two types of end mills were applied to machine the same micro nozzles with different surface quality in this research, respectively. The machined nozzles are inspected by SEM as shown in Figure 2.



(a) Group A, nozzle machined by taper end mill ($a_p$ =0.02mm)



(b) Group B, nozzle machined by ball end mill ($a_p$ =0.02mm)

**Figure 2** Surface topography of nozzle inner surface

### 3. CFD simulation

CFD simulation is used to calculate the variation of thrust and velocity performance for micro nozzles with different surface quality. Residual surface model as illustrated in Figure 1 is utilized for nozzle performance simulation. The simulation process presented had been done with ANSYS-FLUENT 16.1. Nitrogen gas was used as fluid media whose viscosity follows Sutherland law. The nozzle inlet gas temperature was set 300 K. Inlet total pressure was 2MPa.

Nozzle flow field is calculated, and the thrust can be obtained by data post-processing and Equation (1) with the above CFD simulation model. The simulation and calculation results are given in Table 1.

$$F = \dot{m}V_e + (P_e - P_a)A_e \quad (1)$$

where, $F$ is thrust of nozzle, $V_e$ is average outlet velocity of nozzle, $P_a$ is ouelet pressure, $P_e$ is atmosphere pressure.

**Table 1** Nozzle thrust calculated by simulation results

| Nozzle machining end mill type | Thrust (N) |
|---|---|
| Taper end mill(Group A) | 1.83 |
| Ball end mill (Group B) | 1.64 |

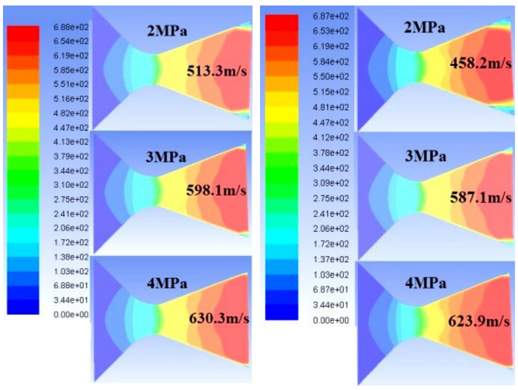



**Figure 3** Contours of velocity magnitude (m/s) (a) Nozzle machining by taper end mill (b) Nozzle machining by ball end mill

As illustrated in Figure 3, average outlet velocity by CFD simulation degrades with the increase of surface roughness under the same pressures. It can be inferred from Equation (1) that reducing outlet velocity leads to the thrust decreasing. However, it would not be sufficient to demonstrate that the nozzle thrust performance variation with surface quality just through CFD simulation. For micro nozzle, thrust is the foremost index of nozzle performance evaluation. Thus, further actual thrust tests for machined nozzle are necessary to carry out.

### 4. Thrust test

A new thrust measuring apparatus was designed and manufactured with multipurpose force sensors and accelerometers of Kistler Company as shown in Figure 4. The force sensor used piezocrystal as a detector to convert the thrust of nozzle into electric signals. The measured electric signals were exactly proportional to the force loaded. Force sensors resolution was 2.44mN.

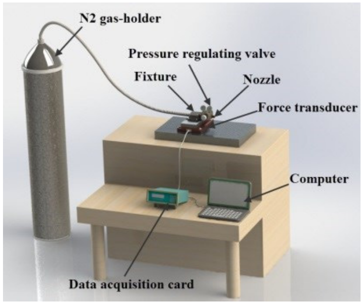



**Figure 4** Thrust measuring apparatus

The thrust was tested with the above thrust measuring apparatus. Figure 5 presents the variation of thrust with the time and the comparison results with the simulated values.

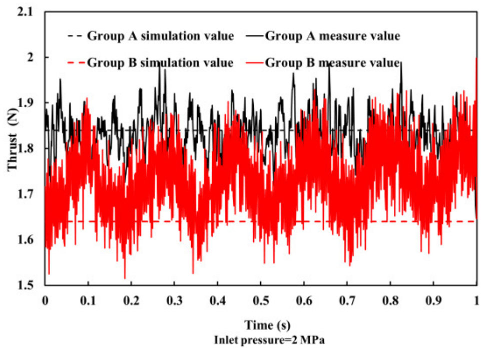



**Figure 5** Comparisons of simulation value with experimental data

### 5. Conclusions

From simulation results, it can be concluded that as surface roughness increases, average outlet velocity, nozzle thrust decreases. Actual thrust test shows that thrust of nozzle machining by taper end mill has better surface quality and large thrust than that machined by ball end mill. Taper end mill could be a good choice for nozzle finishing process. Thrust of nozzle of Group A has the minimum fluctuation compared with that of Group B, due to small surface roughness.

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