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Effect of laser scan speed on surface temperature, cutting forces and tool wear during laser assisted machining of Alumina

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Abstract

This paper deals with the machining of alumina ceramics by employing high intense laser source as pre-heating tool and machined at different cutting conditions to study the feasibility of laser-assisted machining (LAM) process. To understand the thermal response of the ceramics to laser heating, extensive heating studies were carried out to select the laser and machining parameters for LAM. The preliminary studies show that the work surface temperature mainly influenced by the laser power and scan speed.Based on the temperature results obtained from the heating studies the experimental conditions for LAM were selected. The LAM results were compared with conventional machining and presented in terms of cutting force, specific cutting energy and tool wear.It was observed that the increase in surface temperature above 850°Cresulted in reductionof cutting forcesand tool wear.

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*Keywords:*alumina;laser assisted machining; material removal temperature; Nd:YAG laser;scan speed;

Nomenclature

LAM	Laser assisted machining
CBN	Cubic boron nitride
Vz	Laser scan speed or tool traverse speed (mm/min).
P	Laser average power (W)
Doc	Depth of cut (mm)
d_l	Laser spot diameter (mm)

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1. Introduction

Ceramics are widely used in critical engineering application such as mechanical seals, bearings, gas turbine engine components and cutting tools, particularly high purity alumina arebeing used as wear resistant parts, thermal and electrical insulators [1-4].The ceramics like silicon nitride, alumina, mullite, and zirconia are considered as difficult to machine materials due to their brittle failure, crack on finished surface and difficulty to carry out the secondary process [5-8]. The ceramics are machined by using various advanced machining processes such as diamond grinding, abrasive water jet machining, ultrasonic machining, electrochemical machining, electric-discharge machining and cryogenic machining. The above methodswere limited to disadvantages like low material removal rate (MRR), expensive tool, high tool wear, time consuming and low surface finish[4-10]. Over the last three decades a lot of work has been reported on thermally assisted machining (TAM)of difficult to machine materials. In TAM the work materials are preheated by an external energy sourceupto softening temperature and then machined by conventional processes. The preheating reduces the tensile strength, hardness and strain hardening of work material.The various heat sources such as oxyacetylene torches, induction coils, plasma and laser are used by various researchers and reported that plasma and laser are the proficient heating source for TAM of ceramics [6-12]. The Plasma Assisted Machining (PEM) approach also has difficulties in controlling the spot size; the heated area which may lead to a layer with microstructure alteration remained in the machined surface. The instantaneous heating capability of laser with focused beam is ideally suited for the material difficult to process by mechanical machining. Hence the laser has been considered as an effective heating source for thermally assisted machining of hard materials [10-12].

Many investigators have studied the viability of Laser Assisted Machining (LAM) of ceramics like alumina, mullite, silicon nitride and zirconia [11-18]. However,LAM of ceramicssuccessfully for industrial applicationsare rather difficult. A key to the success of LAM is its ability to control the temperature field at the machining zone of the workpiece during operation. Hence it is highly imperative to study the thermal behavior of alumina ceramic to laser heating for choosing the laser and machining parameters in LAM. The main operating parameters in laser assisted machining are laser power, spot size, laser-tool lead, cutting speed, and feed.A series of experiments were designed for analyzing the effect oflaser power (P) and laser scan speed (Vz)through preheating study and machining of alumina (Al_2O_3)ceramics. The main objective of this paper is to find the laser operating window to obtain the work surface temperature above 850^{o}C and the machining parameters for LAM.

2. Experimental setup

The experimental setup for LAM consists of a 2 kW Nd: YAG continuous wave laser of wavelength 1.06 µm and a precision high speed lathe. The laser source is connected through an optical fiber cable to a focusing head with 160 mm focusing optics. The laser head is integrated to precision high speed lathe 'GedeeWeiler(MLZ 250 V)' using a special fixture which is designed and fabricated to hold the laser delivery head and pyrometer. The fixture is designed such that the laser beam can be irradiated at 45°- 90° from tool and radially to the workpiece. Compressed air at 4 bar is used to protect the laser optics from the fumes and debris resulting from the heating and cutting processes. Online recording of surface temperature wascarried outfor all the cases of heating study and LAM using Williamsondual wavelength pyrometerof range between 500 and 2000^{o}C. The cutting forces are measured using Kistler dynamometer (9257B) which was mounted on the tool post. Fig.1illustrates the experimental set up developed for the laser assisted machining of Al_2O_3.This study consists of two phases:laser preheating studies and laser assisted machining.

Aluminium ceramics (Al_2O_3)of 100 mm length and 20 mm diameter with density 3.95 g/cm^{3}was used in the current study.The chemical composition of alumina is tabulated in Table 1. Each experiment was carried out using a new CBN tipped insert CNMA120408 (grade BN 500, made by Sumitomo).

Table 1 Chemical composition of alumina ceramics

Elements Unit	Al_2O_3 Wt%	Sio_2 ppm	Ca ppm	K ppm	Mg ppm	TiC ppm	Cr ppm	Ne ppm	Fe ppm
Quantity	99.9	10	2	20	<1	<1	<1	12	6

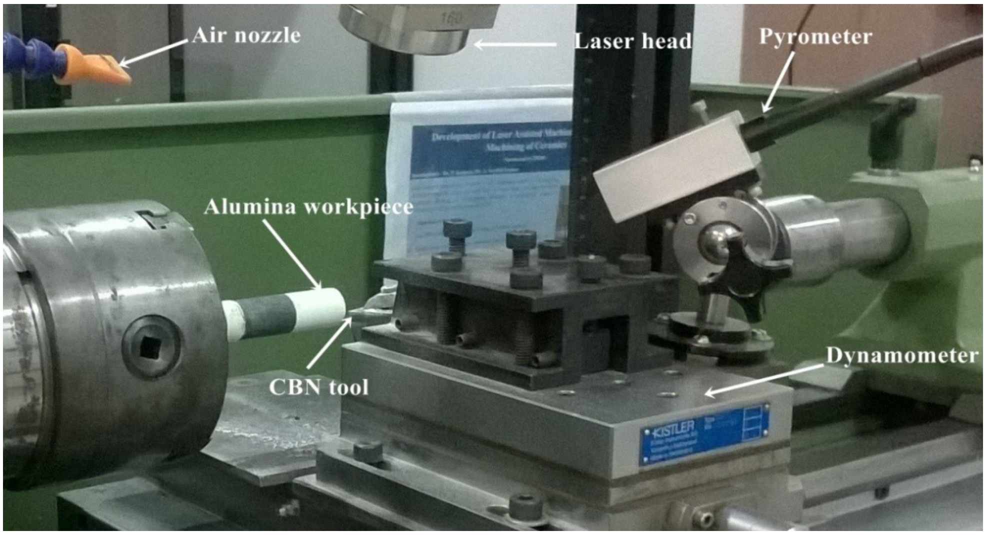

Figure 1 Typical Laser assisted machining setup

2.1.Laserpreheatingstudy

The laser pre heating experiments for alumina ceramic wereplanned based on the previous studiesreported in the literature [11-18]. The operating parameters selected for the present study are shown in Table 2 and Table 3.The laser pre heating experiments were performed by varying the laser power and scan speed. In each experiment the temperature histories is recorded with respect to timeand typical values are shown in Figures 2 and 3.The results obtained from the thermal study gives a clear guideline for choosing the parameters for LAM.

Table 2: Operating conditions for laser power based preheat studies

Expt. no	P (W)	Vz(mm/min)	Rotational speed (RPM)	Avg surface temp(°C)
1	0	45	1500	31
2	200	45	1500	800
3	350	45	1500	1278
4	500	45	1500	1400
5	700	45	1500	Above 2000

Table 3: Operating conditions for laser scan speed based preheat studies

Expt. no	P (W)	Vz (mm/min)	Rotational speed (RPM)	Avg surface temperature (°C)
1	350	15	500	1400
2	350	25	834	1330
3	350	35	1167	1300
4	350	45	1500	1278
5	350	55	1834	1220
6	350	65	2167	1174
7	350	75	2500	920

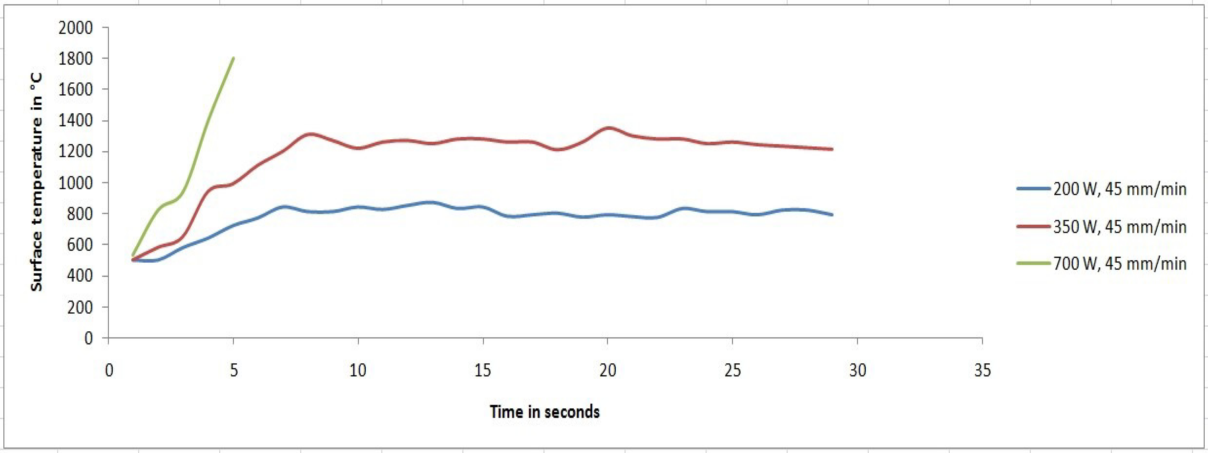

Figure 2 Surface temperature variations along the heating length

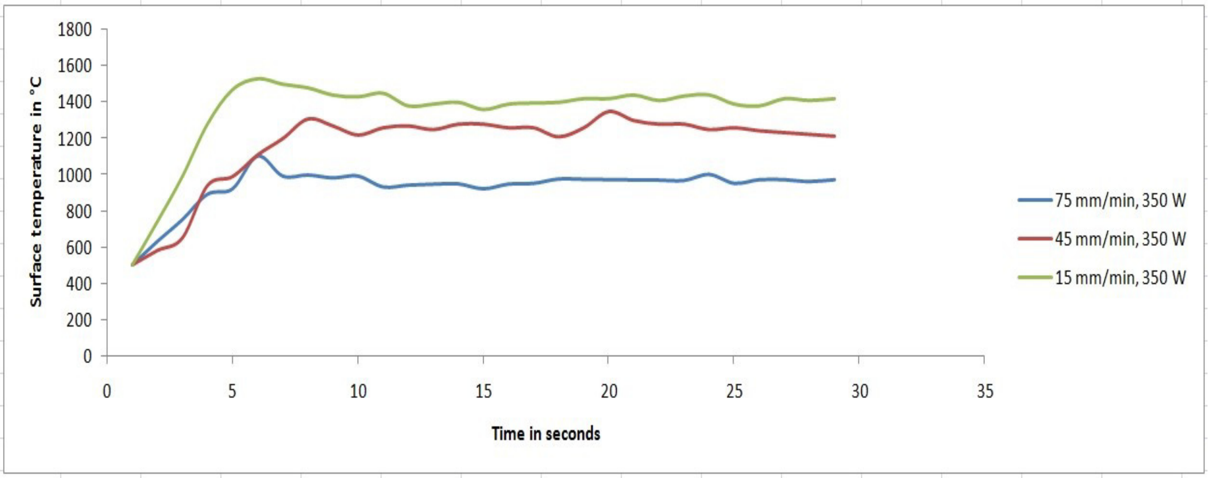

Figure 3 Surface temperature variations along the heating length

2.2 Experimental test matrix of LAM

The parameters were chosen based on the preliminary preheating studies conducted on alumina ceramics. The minimum softening (glassy phase transformation) temperature for the alumina ceramics is 850° C. The preheating results revealed that to achieve the temperature above the glassy phase transformation in moderatelaser power it is required to select the process parameters like feed in lower range between 0.01 and 0.04 mm/rev and cutting speed in moderate range between 15 and 65mm/min. The laser scan speed (Vz) is considered as an important parameter in the present study hence the LAM experiments were conducted at various laser scan speeds. The other process parameters such as laser power, feed, depth of cut, spot size were kept constant as 350W, 0.03mm/rev, 0.3 mm and 2mm, respectively. The laser scan speed is varied between15 and 65 mm/min by changing the rotational speed of workpiece. The experimental matrix for LAM of ceramic is shown in the Table 4.

Table 4: Experimental matrix for LAM

Ex. no	P (W)	Vz (mm/min)	Rotational speed (RPM)	Feed (mm/rev)	DoC (mm)	AvgTemp(°C)
1	350	15	500	0.03	0.3	1400
2	350	25	834	0.03	0.3	1330
3	350	35	1167	0.03	0.3	1300
4	350	45	1500	0.03	0.3	1278
5	350	55	1834	0.03	0.3	1220
6	350	65	2167	0.03	0.3	1174
7	0	45	1500	0.03	0.3	-

3. Results and discussion

3.1. Effect of Laser power on surface temperature

The laser power is one of the major factors which influence the surface temperature of the workpiece drastically during LAM. By keeping all the other parameters at constant level as mentioned earlier and only the laser power was varied in this set of experiments. The laser power was varied from 0W (conventional), 200W, 350W; 500W and 700W then corresponding surface temperature obtained were recorded using an infrared pyrometer. Figure 4 shows the average surface temperature obtained at various laser power levels. The change in surface temperature depends on the energy deposited by laseron the work piece [18]. The result shows that as the laser power increases the surface temperature increases. At 200W laser power the surface temperature is gradually increases and reaches maximum of 900° C at the end of 30 sec.At high power, 700W the surface temperature exceeds 2000°C which is the maximum limit of the pyrometer used in this study. At 350W laser power the average surface temperature is 1278°Cwhich is found to be more suitable for LAM machining.

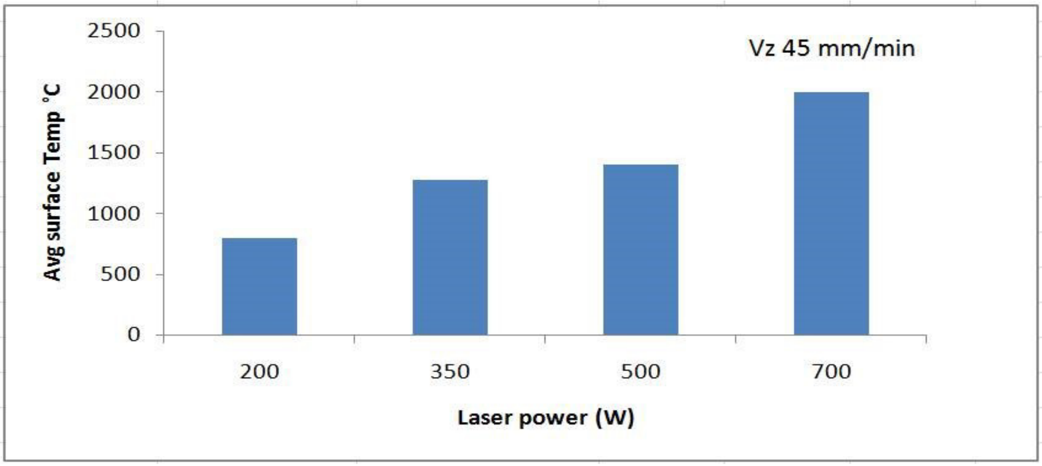

Figure 4 Average surface temperaturefor different laser powers

3.2. Effect of laser scan speed on surface temperature

The effect of laser scan speed on average surface temperature is depicted in Figure 5. The results indicate that the surface temperature decreases with the increase in scan speed. This trend could be attributed to the fact that as the laser scan speed increases the time available for the energy absorption decreases which resulted in low surface temperature. At fixed laser power of 350 W, maximum temperature of 1400°C was obtained at low scan speed of 15 mm/min whereas at high scan speed of 75 mm/min the average surface temperature was 920°C. The desired surface temperature for the alumina ceramic is between 950 and 1400°C [4-9].The surface temperature histories of lower scan speed (15mm/min) shows high range of average temperature around 1400°C which is not suitable for LAM, which is thermal durability limit for CBN inserts [13, 18].Since the tool material used in current studies is a low

CBN content with ceramic binder the heat resistance is lower than that of high CBN. Hence for the LAM experiments the laser scan speed in the range between 15 and 45mm/min was chosen.

Table 5 Output responses for LAM

Case	Fx(N)	Fy(N)	Fz(N)	Uc (J/mm3)	Tool wear
1	21.48	41.22	24.89	4.58	334
2	13.38	26.9	10.72	2.99	273
3	6.1	22.44	5.31	2.50	248
4	4.79	12.41	4.78	1.38	103
5	5.96	16.79	2.09	1.87	106
6	8.51	17.69	5.35	1.97	110
7	23.66	43.59	20.74	4.84	369

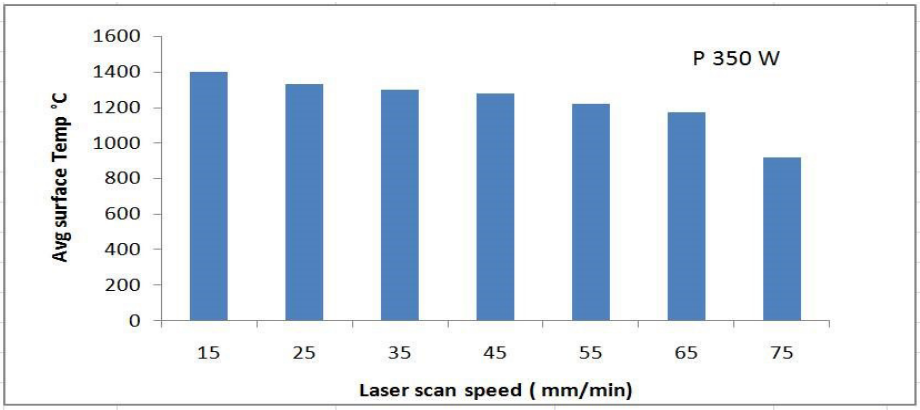

Figure 5 Average surface temperature for different laser scan speed

3.3. Triaxial Cutting forces

Figure 6 shows the triaxial cutting forces recorded for a machining length of 12 mm during conventional (without laser) and LAM machining. It is very clear from the figure that the forces increase with the machining length. The tool wearprogresses during machining which alters the tool geometry and ultimately results in increased cutting forces. During the conventional machining the forces increase very rapidly due to high tool wear rate. However, during the LAM the cutting forces are more or less steady when compared to conventional machining.

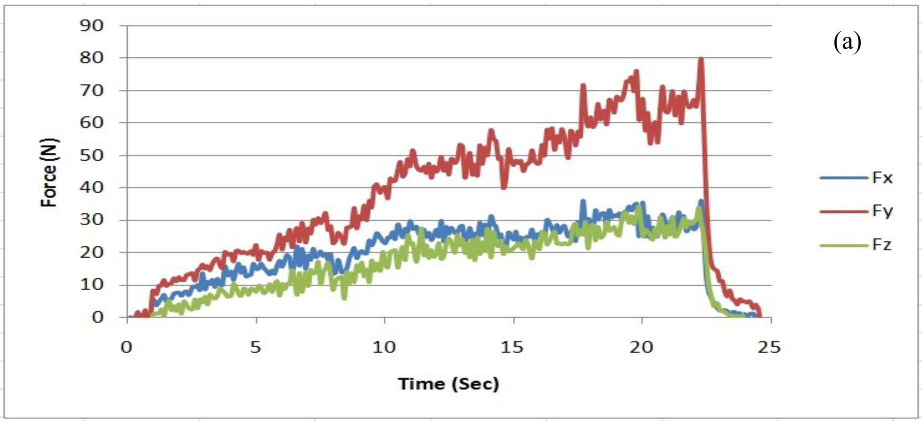

Figure 6 a) cutting force history along the machining time for convectional machining at 45mm/min Laser scan speed.

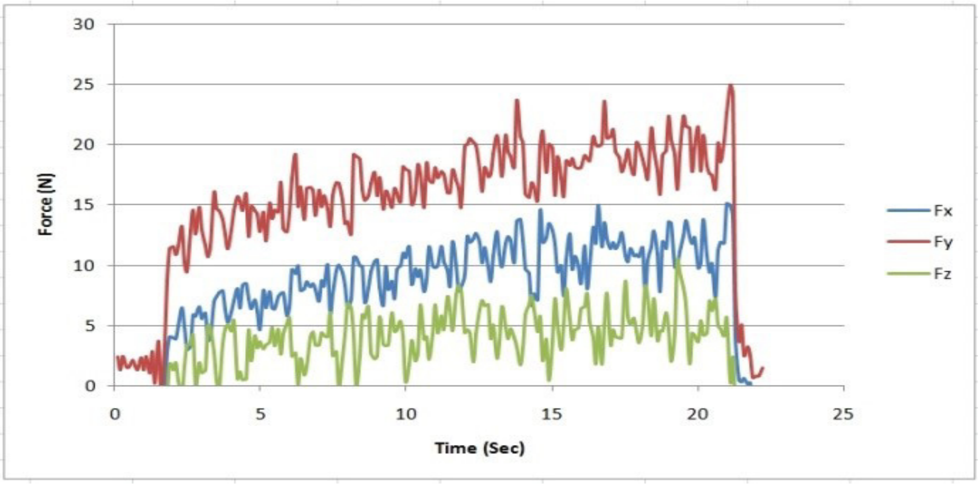

Fig. 6 (b)cutting force history along the machining time for LAM at 45mm/min, 350 W

The average triaxial cutting forces for different laser scan speeds are shown in the Figure 7. It shows that as the laser scan speed is increased from 15 to 45mm/min the main cutting force (Fz) decreased from 24.89to 4.78N(80% reduction).It is to be noted that even though work surface temperature is high (1400°C) at laser scan speed of 15 mm/min high cutting forces were observed. The possible reason could be at temperature above 1350° C the CBN loses its thermal durability and the tool wear increases very rapidly [18]. The average surface temperature at laser scan speed of 45 mm/min is 1278°C, which is above the glassy phase transition temperature (850°C) and below the tool thermal durability limit. It was also observed that beyond 45mm/min laser scan speed the cutting forces start climbing up. At high laser scan speed the surface temperature of ceramic decreases due to less laser material interaction time and at the depth of cut the temperature would be below the softening temperature. Further, it was also found that the thrust force (Fy) value is high for all the experiments when compared tothe main cutting force (Fz) and this could be due to the size effect. In order to compare the cutting forces with conventional machining an additional experiment (Expt. 7) was performed at the machining conditions corresponding to lower forces in LAM without laser heating. The average cutting force reduction of about 80% was observed for LAM when compared to conventional machining. Thus, it is very evident that the surface temperature plays major role on cutting forces, and tool wear in LAM.

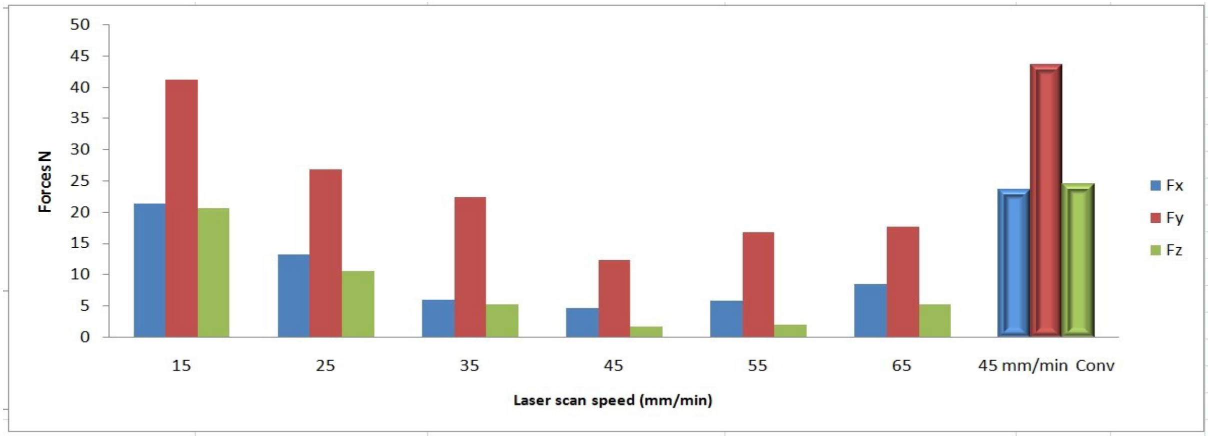

Figure 7 Average triaxial cutting forces for different operating conditions

3.4. Specific cutting energy

The energy required to remove unit volume of the material is known as specific cutting energy (Uc). However, in LAM thermal softening is a major factor which influences the cutting forces, and specific cutting energy. The main objective of the laser heating is to elevate the temperature at the cutting zone above the glassy phase transformation temperature.The specific cutting energy of LAM at different laser scan speed and also the nominal condition is compared with conventional machining in Figure 8. The Uc decreases with the increase in laser scan speed up to 45 mm/min and beyond which it starts increasing. Since the Uc is the ratio of main cutting force to area of undeformed chip thickness the reasons stated for the cutting force trend is also applicable for the Uc. The minimum specific energy during LAM of alumina is 1.38 J/mm^{3}and in conventional machining is 4.84 J/mm^3.Approximately 70

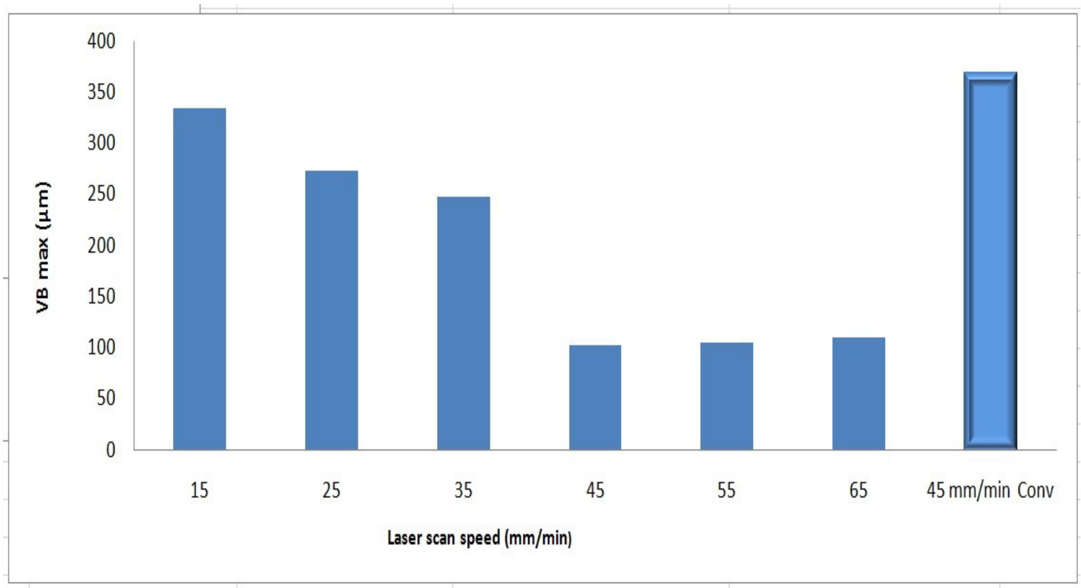

Figure 8 Specific cutting energy for different operating conditions

percentage reduction in cutting energy is found while comparing the conventional and LAM at 350W laser power and 45 mm/min laser scan speed. It is also to be noted that specific cutting energy in LAM is very less compared to the conventional grinding process.

3.5. Tool wear

Figure 9 shows the effect of laser scan speed on flank wear. The maximum flank wear, Vb_{max} is considered in the tool wear studies.Fresh cutting edge is used in every experiment and the inserts were cleaned with acetone before tool wear measurement. It is very evident that the flank wear is very less in LAM when compared to conventional machining.As the laser scan speed increases from 15 to 45 mm/min the flank wear decreases and beyond which it increases. The reason for this trend could be explained from the cutting force results obtained during machining. The cutting forces decrease up to 45 mm/min laser scan speed which results in lower flank wear. It was also noted that the flank wear variation is insignificant at laser scan speed between 45 and 65 mm/min. The progress of tool wear is very rapid in conventional machining (without laser) when compared to LAM. The minimum flank is observedat laser scan speed of 45mm/min.

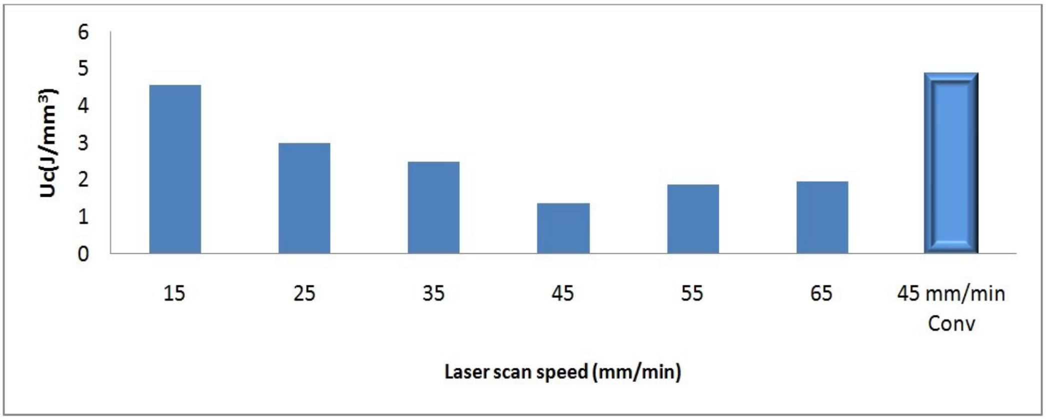

Figure 9 Tool wear for different cutting conditions

4. Conclusions:

The main objective of this paper is study the potential of LAM for alumina ceramics. The following conclusions were drawn from the above experimental results.

- The surface temperature of the ceramic material increases with the increase in laser power and decrease in laser scan speed.
- The optimal temperature (around 1250°C) is obtained at laser power of 350 W and laser scan speed between 35 and 55 mm/min.
- The minimum cutting force is observed during LAM at laser power of 350 W and laser scan speed of 45 mm/min.
- The maximum cutting force and specific cutting energy reduction of about 80% was observed for LAM at identical machining conditions when compared to conventional machining.
- The cutting force and specific cutting energy is reduced from 2 to 3 folds while increasing the laser/tool traverse speed between 15-45 mm/min.
- Tool wear shows significant improvement while increasing the laser scan speed from 15 to 45 mm/min, which is low at laser traverse speed of 45 mm/min.
- The surface temperature plays major role on cutting forces, and tool wear in LAM.

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